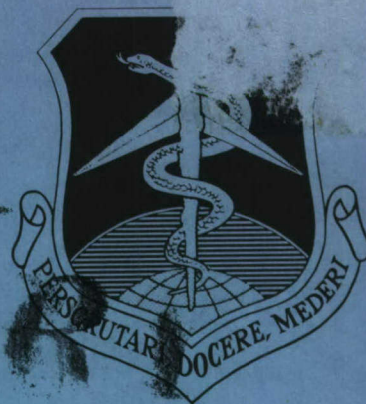


AMD-TR 67-2



PROCEEDINGS OF
FIRE HAZARDS AND EXTINGUISHMENT CONFERENCE

Hosted by
Aerospace Medical Division
Brooks Air Force Base, Texas
23 May 1967

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DIRECTORATE OF RESEARCH and DEVELOPMENT
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
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The experiments reported herein were conducted according to the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

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ABSTRACT

Subsequent to the fire in the space environment simulator at Brooks Air Force Base on 31 January 1967 the Aerospace Medical Division developed fire extinguishing systems and protective clothing for use in oxygen enriched atmospheres. As this was a subject of intense general interest, it seemed appropriate to host a conference to describe and demonstrate these fire extinguishing systems and protective clothing. This document contains the proceedings of the conference which was held on 23 May 1967 and was attended by approximately 300 persons.

**NO OBJECTION TO PUBLICATION ON GROUNDS
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WELCOME ADDRESS

Major General Charles H. Roadman
Commander Aerospace Medical Division
Brooks Air Force Base Texas

I would like to welcome you to Brooks Air Force Base, the home of the USAF School of Aerospace Medicine and the Headquarters of the Aerospace Medical Division. We are very pleased to have such a distinguished group convene this morning and, frankly, quite surprised by the number who have expressed by their presence, interest in this area. As shown by the size of this group, the organizations represented and the agenda, it is apparent that the subject of this meeting is of sincere concern to us all, both in this country and in fact, international. We have accomplished considerable work in the areas of fire ignition and extinguishment and in protective clothing since our unfortunate accident on 31 January. The intent of this conference is to share with you the information which we have gathered, and we have pointed our agenda to meet this goal. In addition, we are very happy to have representatives from the United States Navy, the Veterans Administration, the Royal Air Force and the National Aeronautics and Space Administration on this program.

You can see that the agenda is a full one and the schedule is quite tight, however, we do not intend to permit the schedule to prevent our answering your questions before you leave. We are anxious to have any

information from any conferee, and not just those on the program, because exchange of information is the objective of this conference.

Our research programs which use oxygen enriched atmospheres are presently in a state of suspension contingent upon certain modifications--removing fire hazards, providing fire extinguishing systems, and the development of protective clothing for our future research efforts. We intend to resume these programs in the near future but not until we have provided reasonable and acceptable systems which will prevent future accidents in these environments.

I would like to express my appreciation to the contractors who have worked closely with us during the past two months: The Southwest Research Institute, the "Automatic" Sprinkler Corporation of America, Fenwal Incorporated, and Pyrotronics; to our associates from the Air Force laboratories at Wright-Patterson AFB and to our own personnel at Brooks. This has been an outstanding team in the opinions of all of us. They spent many long hours installing and testing the fire extinguishment systems and developing the protective garments.

Again, I want to express our appreciation for your attendance at this conference. I trust that the accommodations and other administrative arrangements are satisfactory, and I, with all members of the Division and the USAF School of Aerospace Medicine, am very pleased with your interest and your attendance. I would like to assure you that

this is your conference and to express again our interest in any other ideas , any suggestions , any criticisms that can improve our research program and assure our getting on in the space environment with the least possible hazards .

We thank you for your attendance .

TWO MAN SPACE ENVIRONMENT SIMULATOR ACCIDENT

Colonel A. G. Swan
Director of Research & Development
Aerospace Medical Division
Brooks Air Force Base Texas

Thank you, General Roadman. I would like to recognize the Deputy Chief of Staff for Bioastronautics and Medicine, Air Force Systems Command, Andrews AFB, General Don Wenger. I would also like to recognize Colonel James Nuttall, the Commander of the USAF School of Aerospace Medicine, whose facilities we are using today. I would like to introduce Dr Hubertus Strughold, the Chief Scientist of the Aerospace Medical Division, and Wing Commander Allen Crawford from the Royal Air Force stationed at the British Embassy in Washington. We will now proceed with the program.

I would like to describe for you the results of the investigation of the accident which occurred at Brooks AFB on 31 January 1967. I will use a series of documentary photographs that were taken two and a half hours following the fire. These photographs will take you from the outside of the chamber to the inside of the chamber so that you will have an idea of the extent of the burning and the pattern of flame propagation. Figure 1 is a view of the high bay area in Building 170. The chamber is located in the upper right corner. This particular chamber has a lock (the first part) and a test cell approximately 12 feet by 5 feet as shown in Figure 2. The test cell is roughly twice the size of the

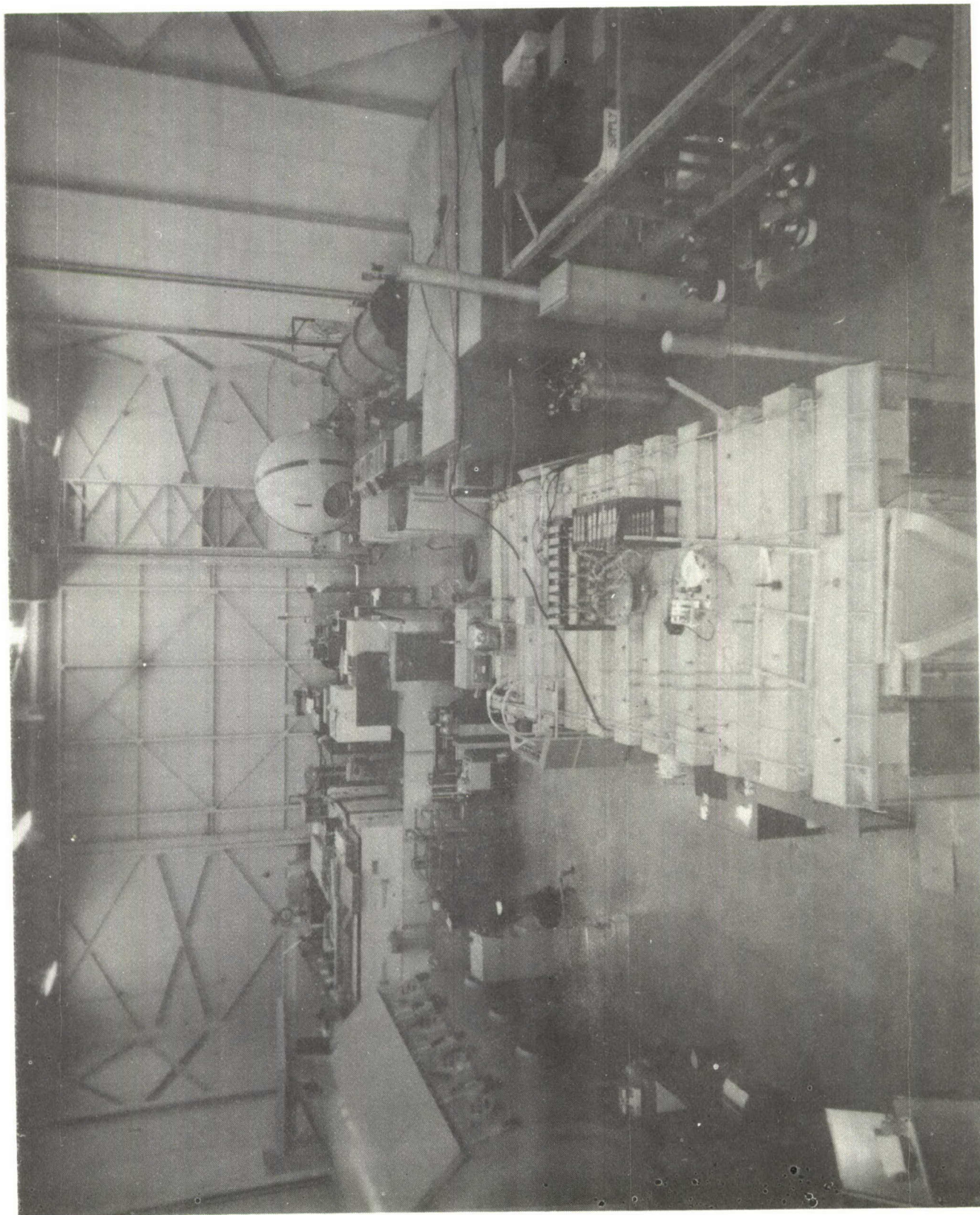
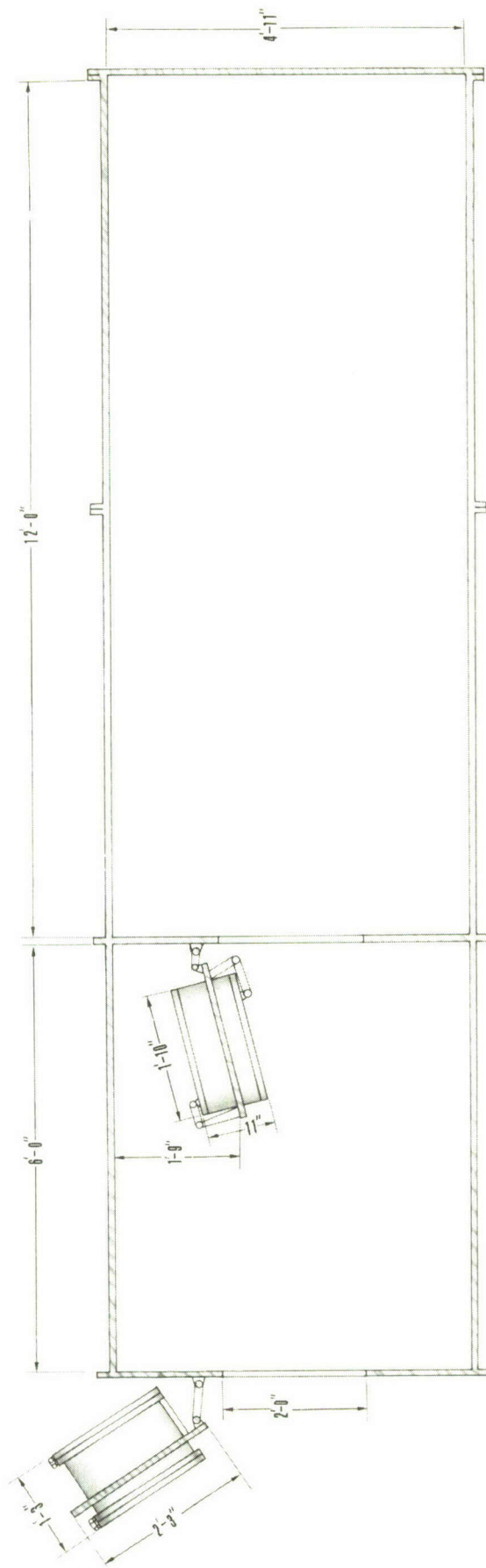


Figure 1 High Bay Area



TWO MAN ENVIRONMENTAL TEST CELL
 ELLIPTICAL CYLINDER-380 cu ft IN VOLUME
 AIR LOCK-190 cu ft

Figure 2 Schematic of Test Chamber

air lock. The right corner of the chamber door is very sooted (as shown in Figure 3) where flames were seen coming from the chamber. Some of the debris in the front portion of the lock was partially burned. This material was taken in by the airmen in order to clean the animal cages. Figure 4 shows an oxygen hose and a helmet that was located in the lock. Figure 5 shows the left side of the lock. There is some uneven burning demonstrated--very intense burning around the top of the oxygen hoses and hardly any burning in the loop a little lower down. Three cages of mice which had been put in the lock are also shown. Figure 6 is a closer view of the oxygen regulator. When the material was chipped away from the switches and when the oxygen regulators were checked, they were found to be completely functional.

Figure 7 is a view into the test cell which shows packages of refuse that had been taken from the trays beneath the sixteen rabbit cages inside the chamber. Figure 8 is a view of the right side of the test cell immediately in back of the bulkhead. There was no burning at all of this hose and only a little sooting. Figure 9 is another view of the left side and rear of the test cell. Notice that some of the cage doors are open. Figures 10 and 11 are some views of some of the materials which the airmen inside were working with--a dust pan and broom which had been used for cleaning, a lamp and some of the animals which were out of their cages. The laboratory stool that

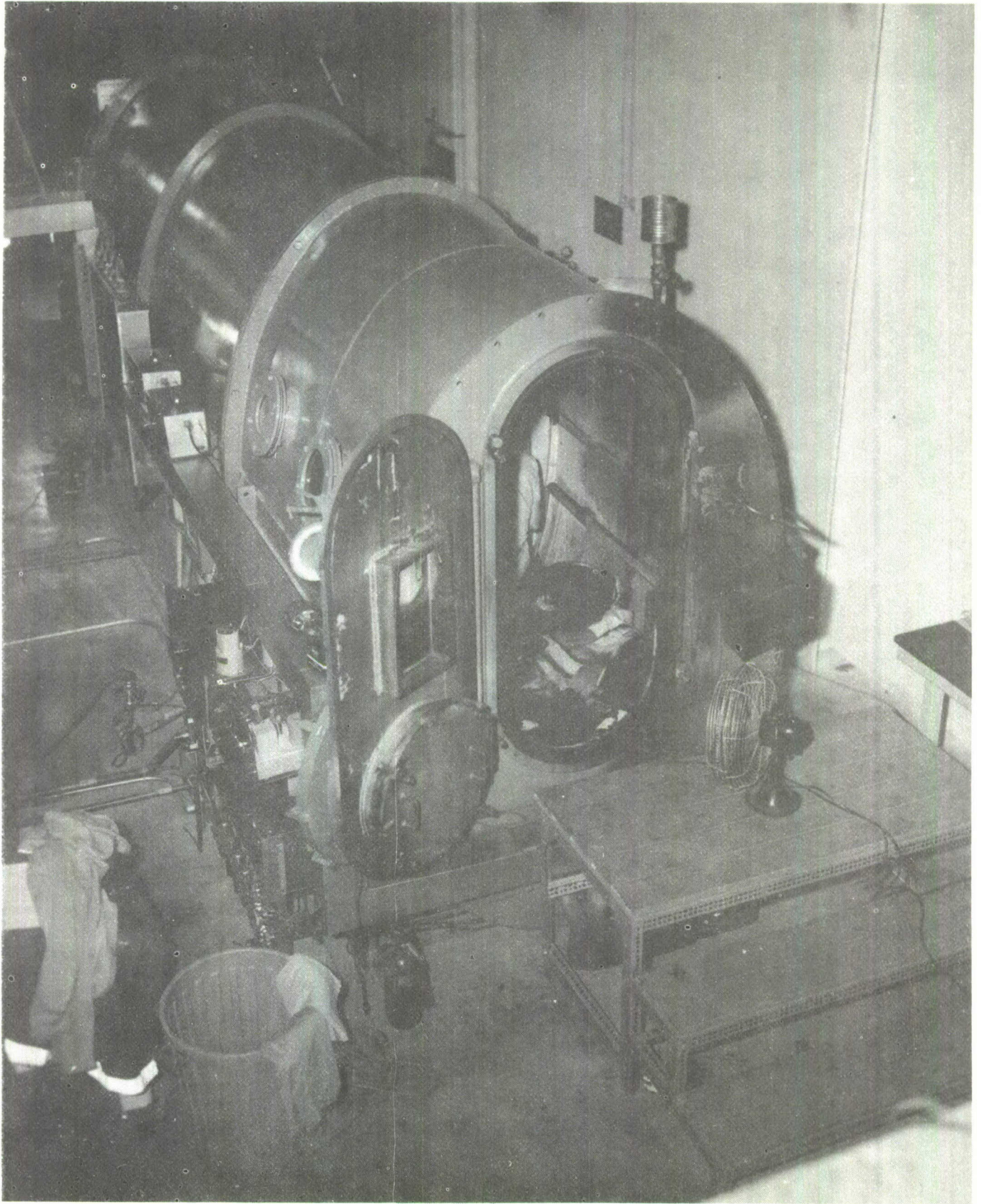


Figure 3 Front View of Test Chamber



Figure 4 Right Rear Corner of Lock



Figure 5 Left Side of Lock



Figure 6 Oxygen Regulators in Lock



Figure 7 View into Test Cell

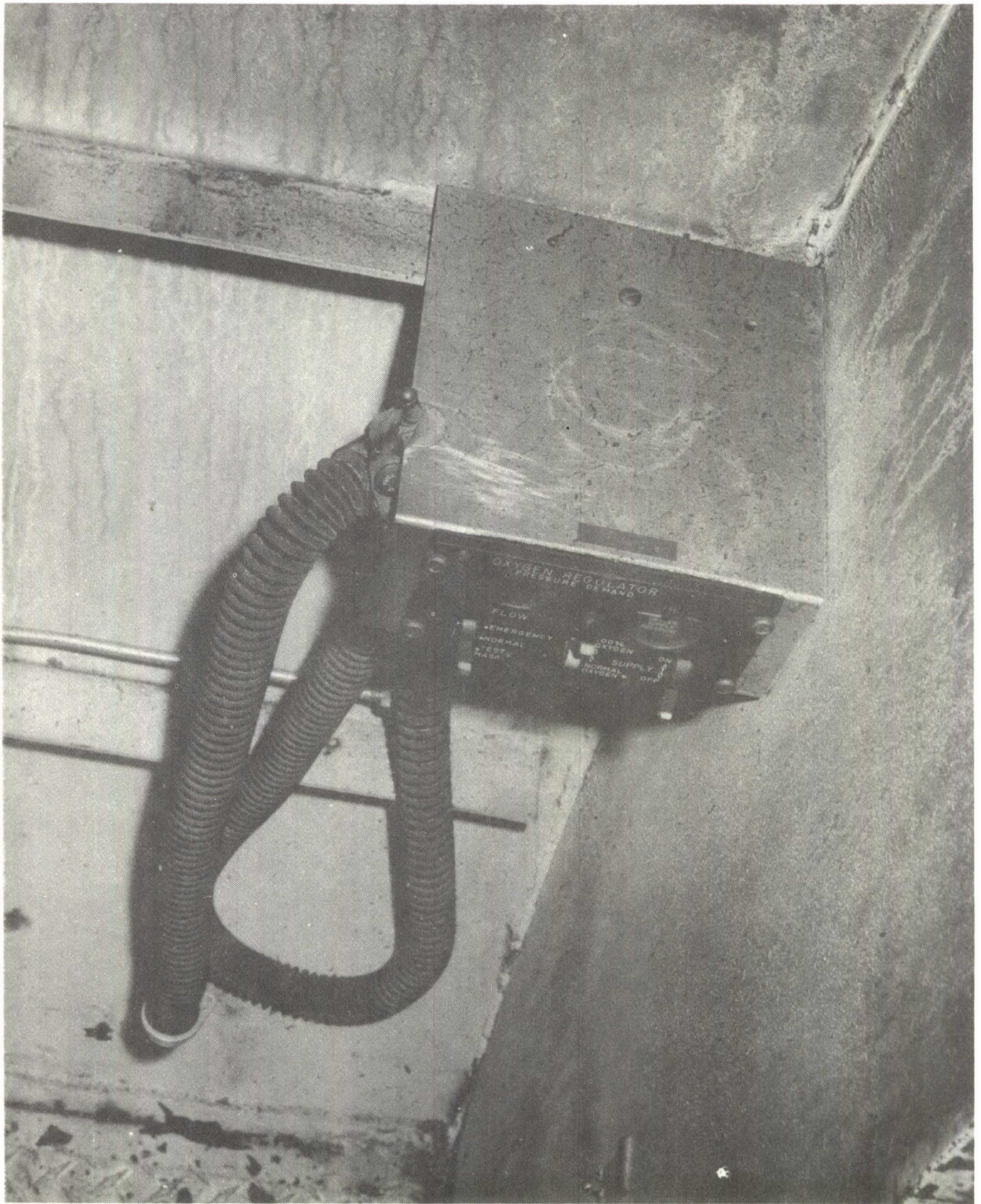


Figure 8 Test Cell Oxygen Regulator



Figure 9 Left Side of Test Cell

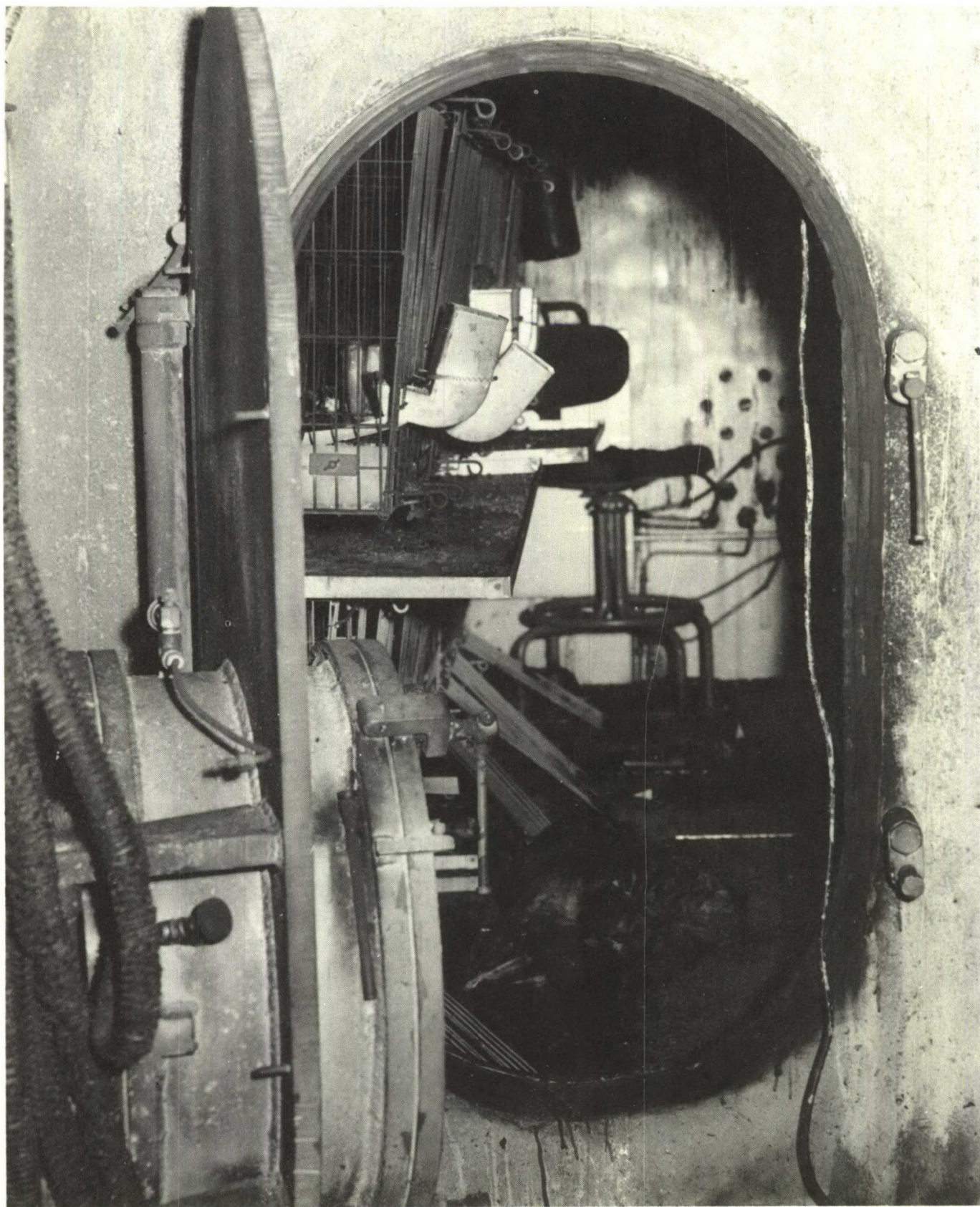


Figure 10 Center of Test Cell

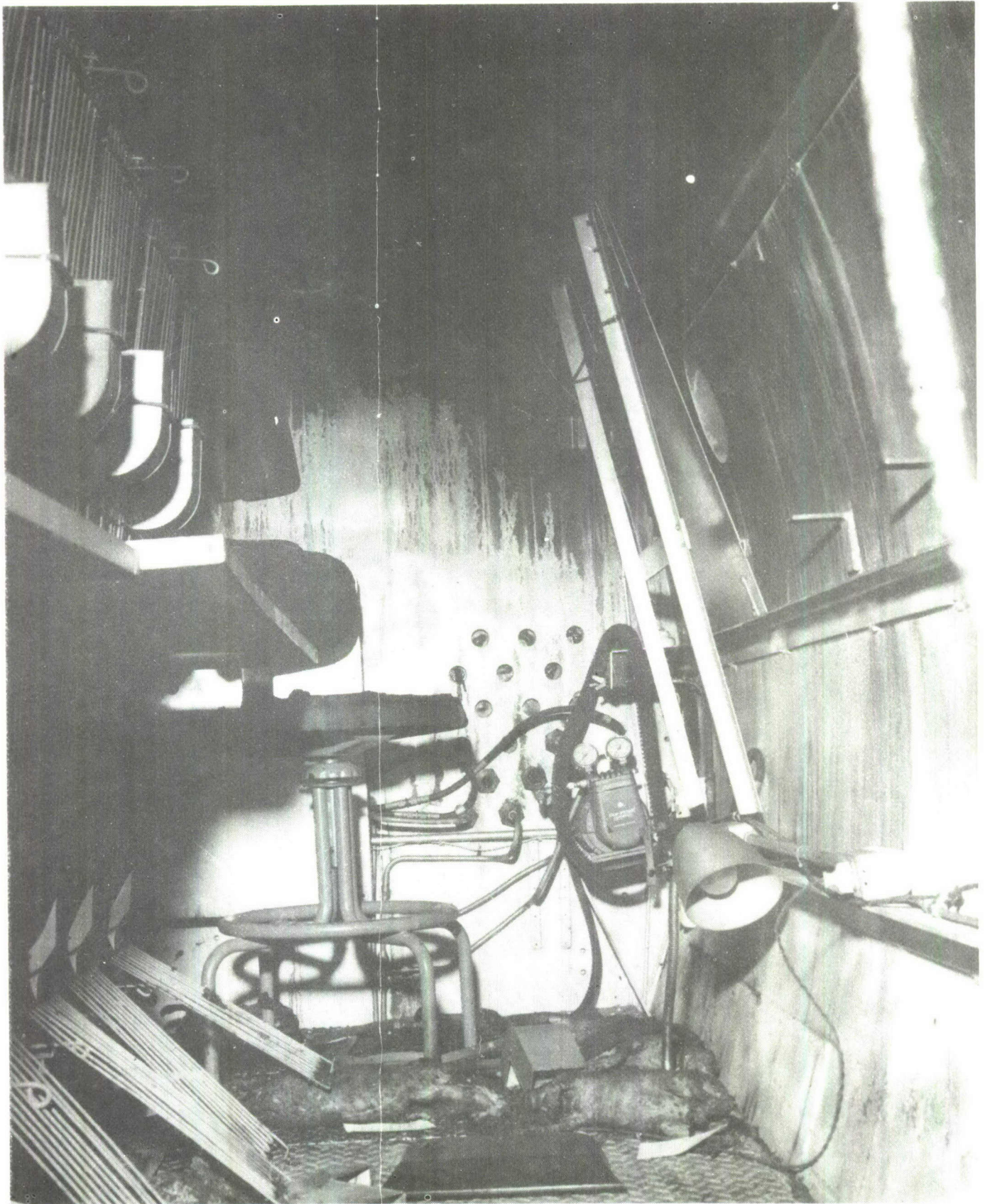


Figure 11 Right Side of Test Cell

had burned is responsible for most of the sooting because the air circulation at the time was going up at that end of the chamber. Figure 12 is a closer view of some Teflon insulated wire which did not burn and grommets on a junction box which did burn. The sooting inside this junction box (Figure 13) is a result of the smoldering grommets. Figure 14 shows part of a communications cord that burned partially. There is some deformation in the microphone, however, this rubber insulated communications cord did not burn.

Let me review for you some of the activities that happened outside of the chamber. On the morning of the 31st of January at about 8:18 the two airmen went inside the chamber and started to altitude in the lock. The purpose for going inside was to remove animal waste, to feed and water the animals and to perform any actions required by the experimental protocol. The objective of the experiment was to determine the effect of near pure oxygen at $1/2$ atmosphere on the blood forming organs of mammals. The experimental animals were sixteen rabbits in addition to the three cages of mice, about fifty in number, which were to be taken in on the day of the fire. The crew chief sits at the instrument panel (Figure 15) and was in voice contact with the airmen inside. After about twenty minutes of denitrogenation and when they had reached 380 mm of Hg the test cell door was opened and the airmen went inside. There was some discussion with the crew chief about

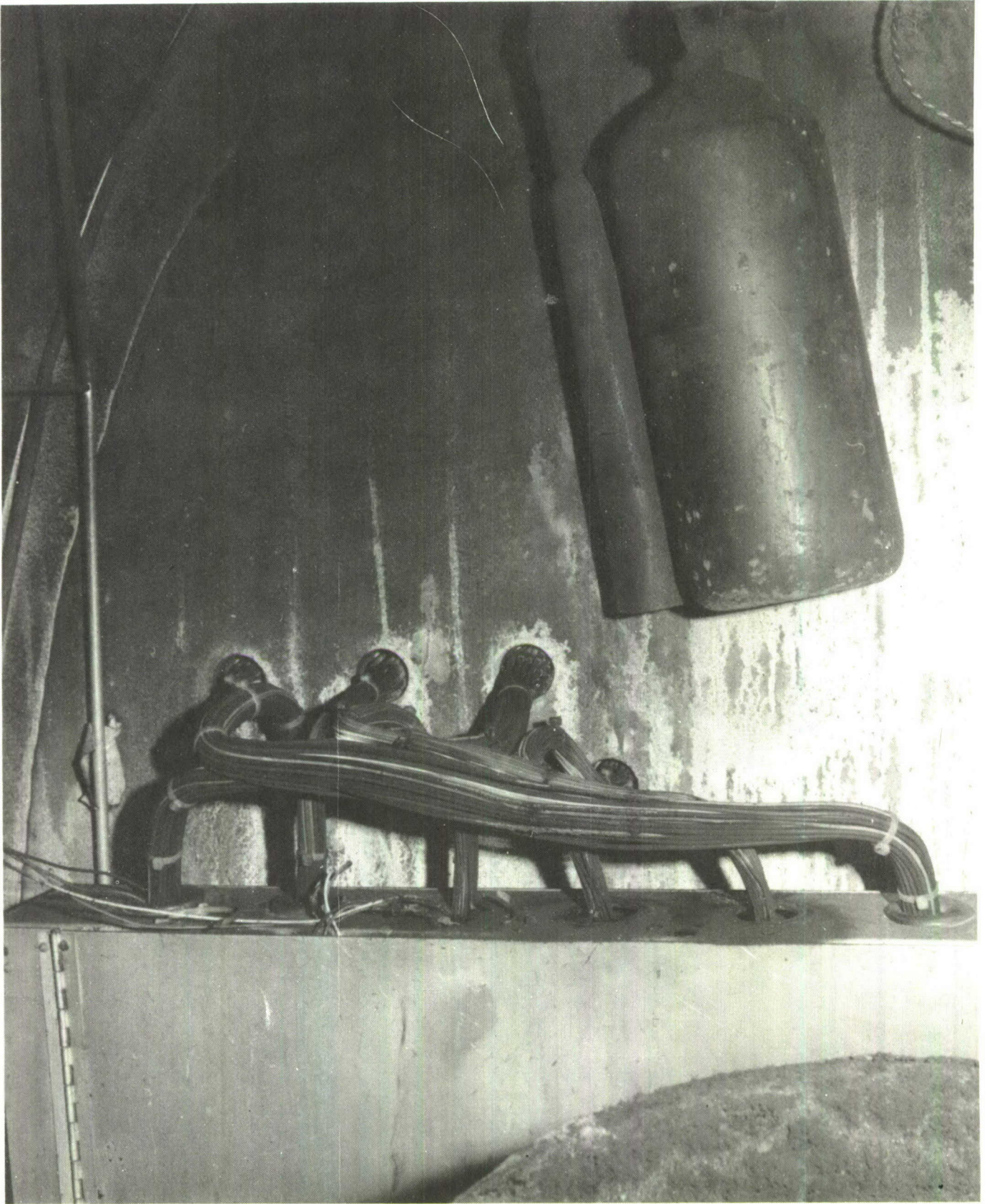


Figure 12 Junction Box in Rear of Test Cell



Figure 13 Interior of Junction Box

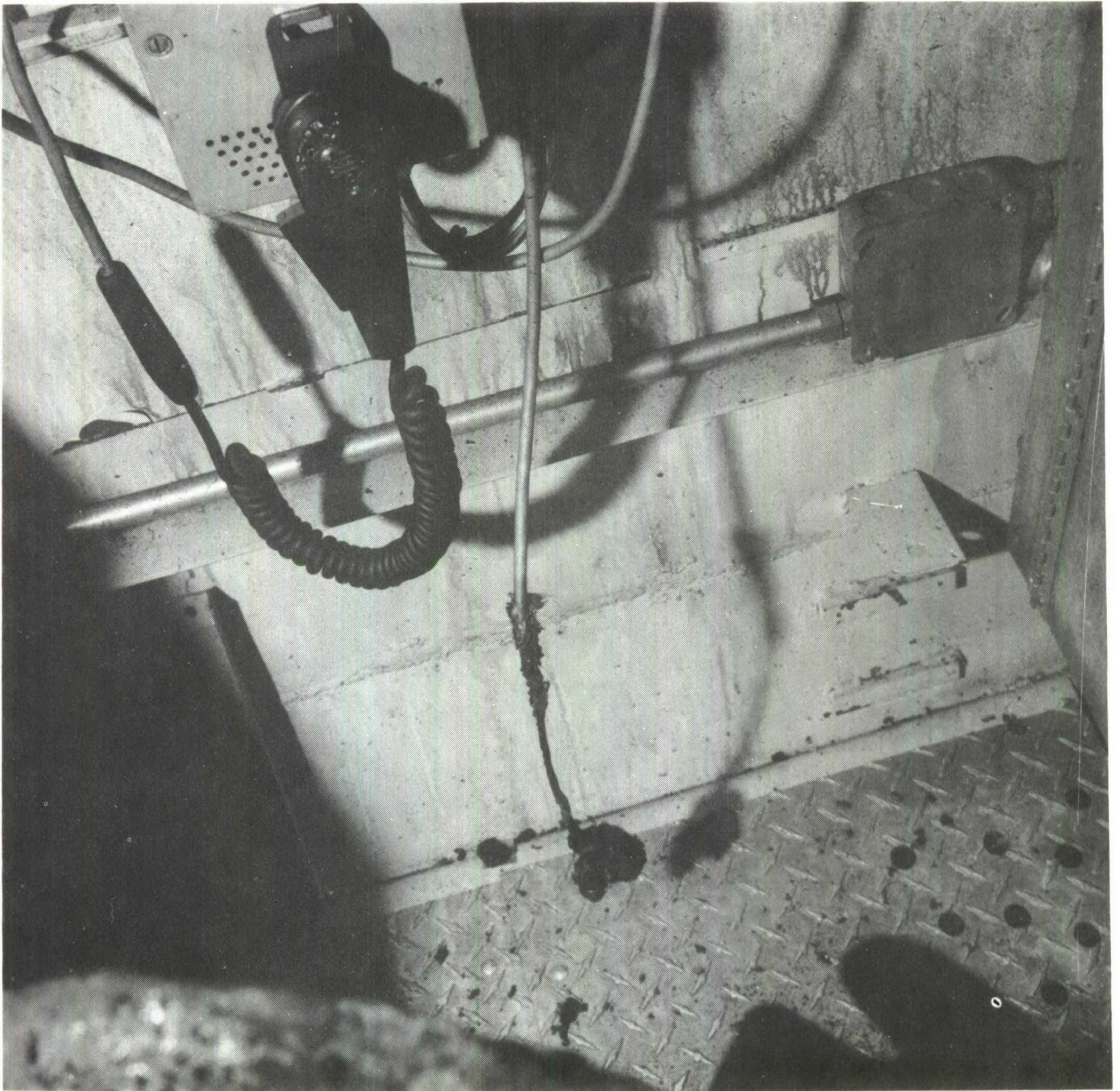


Figure 14 Communication Set in Test Cell

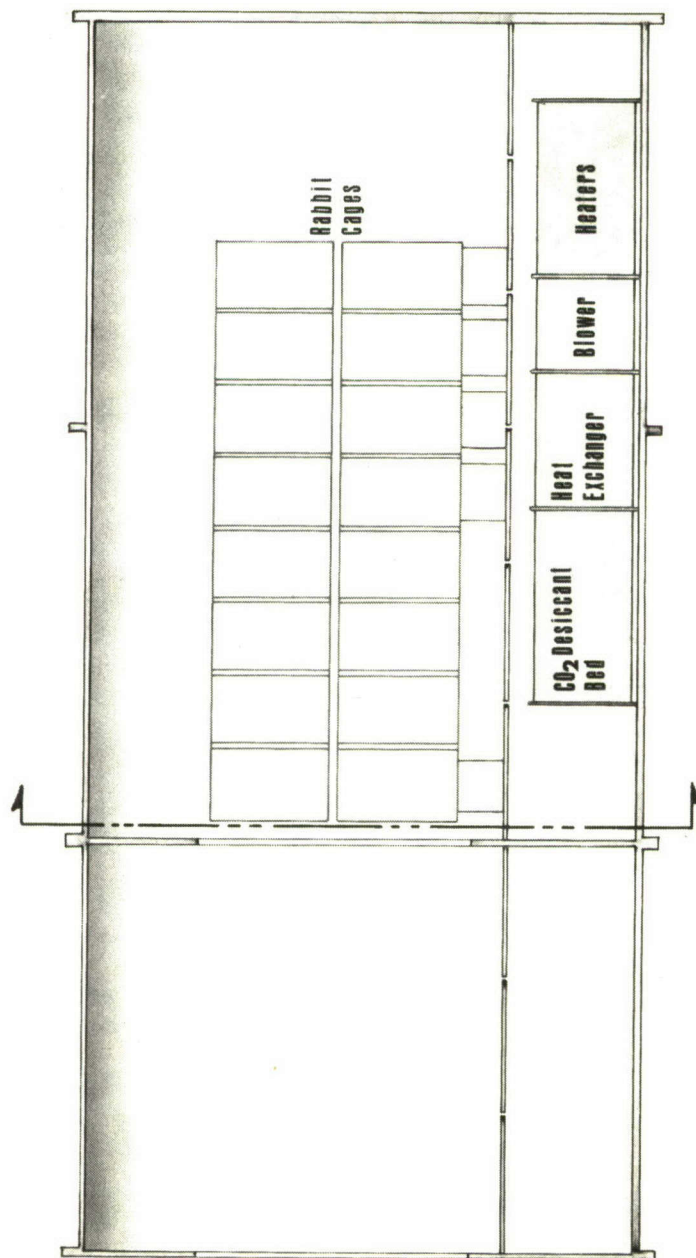


Figure 15 Chamber and Control Panel

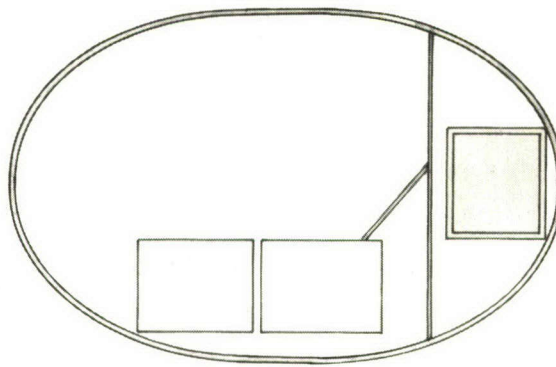
positioning the animal watering bottles because there was hope that they would be able to service the cages on two day intervals rather than daily. The crew chief, after a few minutes, heard a noise that he described as being similar to a cage dropping inside the chamber. At that point, he got up from his console (there was no communication exchanged) and came around toward the front of the chamber and saw the fire through the porthole. He immediately declared the fire, went back to his position at the console and pushed the emergency button which summons the medical officer of the day. He also opened three valves which started the chamber back down to ground level.

Let me now review what we think was happening inside the chamber. In this cross section view (Figure 16) of the chamber the air conditioning duct is shown in its position below the floor. The two rows of rabbit cages are above the floor plates. As to the possible causes of this fire, we know there was a possibility that hydrogen could have been generated because the carbon dioxide removing agent consisted of calcium, barium, and potassium hydroxides. These hydroxides in the presence of water and aluminum will generate hydrogen. Computations indicated, however, that we could have produced only enough hydrogen to accumulate about two percent by volume in the total time available for the reaction. This two percent could have been produced only if all possible reacting agents had been consumed. After going back into the

TWO MAN ENVIRONMENTAL TEST CELL



INSIDE-LEFT SIDE VIEW



END VIEW

Figure 16 Cross Sectional View of Chamber

laboratory to assure that our calculations were correct, we have excluded the possibility that the fire resulted from a combustible atmosphere. In the air conditioning duct we found evidence of a very strong exothermic reaction. Figure 17 depicts the carbon dioxide filter consisting of the hydroxides contained in stainless steel screens. The air conditioning duct is constructed of aluminum. This series of filters (Figure 18) contained several rows of tape to direct the air flow through the hydroxides. Testing performed by the Air Force Materials Laboratory at Wright-Patterson AFB indicated that the aluminum cover experienced approximately 700-800°F. There is some molten stainless steel at several points and some parts of the filter are less damaged than others. These stainless steel ribs were part of the filters. A chemical reaction between pure oxygen and stainless steel will, at a temperature of approximately 2250°F, initiate and sustain itself as long as there is stainless steel and oxygen present. This reaction can be depressed by high concentrations of either water vapor or carbon dioxide. Once the reaction starts it will burn at temperatures between 2300-2600°F. The question was whether this reaction was a primary source of fire or whether it was secondary to the fire. We have calculated that the temperature inside the chamber could have been 800°F within 14 seconds and this far surpasses the auto-ignition temperature of the organic tape which was across the top of the filter. The air conditioning system had active circulation at the



Figure 17 Carbon Dioxide Filter

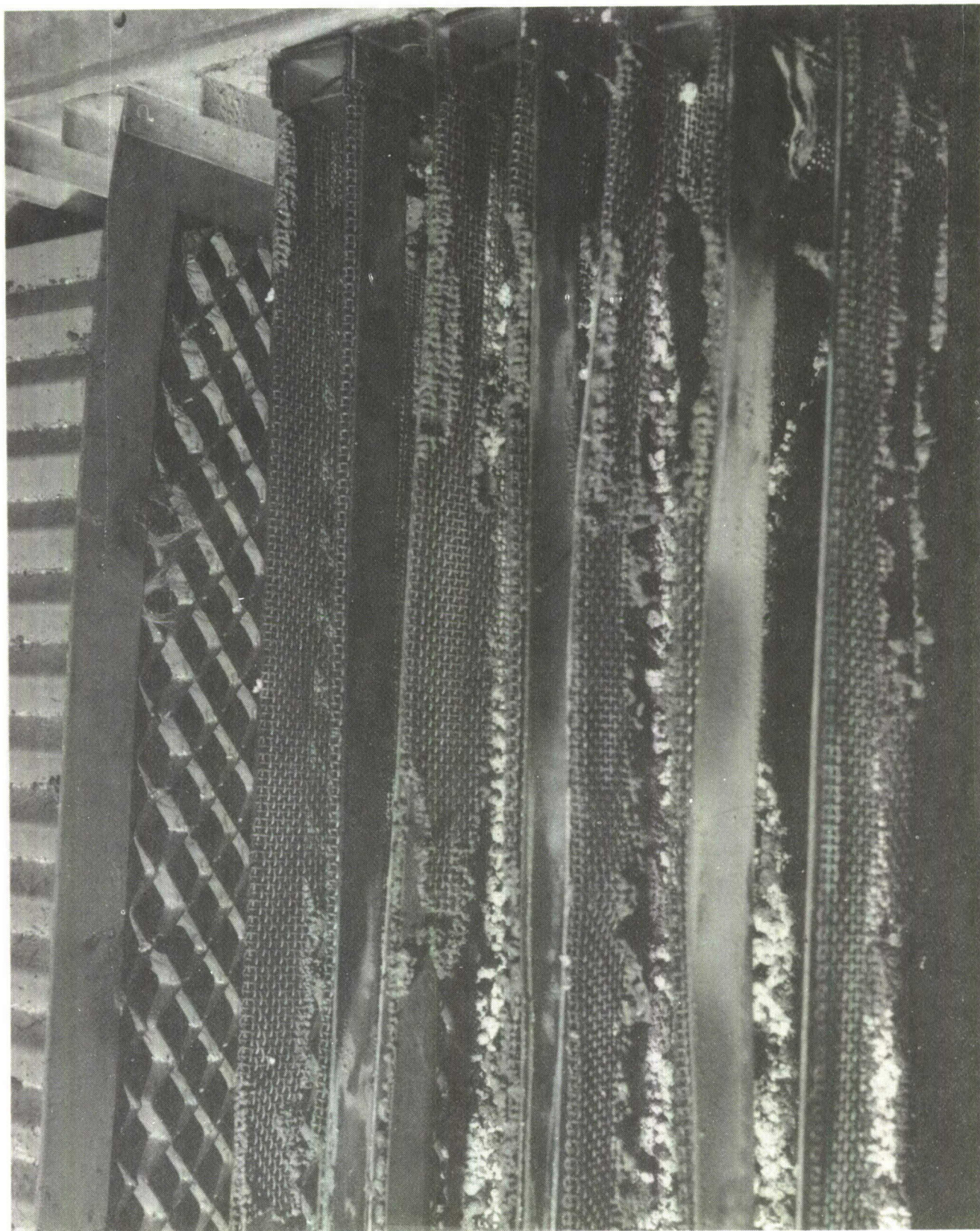


Figure 18 Close Up of CO₂ Filter

time, so the circulation would have taken the hot gases down into the air conditioning duct and would have exceeded the temperature necessary to ignite the tape. This, in turn, (as confirmed by laboratory experimentation) could have burned hot enough to initiate the stainless steel/oxygen reaction. In summary, these were two possibilities of the cause of the fire--the possibility of hydrogen being generated and the evidence of a very strong exothermic reaction that had taken place. We have dismissed both of these--one by determining that hydrogen could not have been generated in sufficient quantities to obtain the minimum four to five percent lean mixture required for an explosive atmosphere and the other by determining that the stainless steel/oxygen reaction very likely started secondary to the fire.

Figure 19 shows the position of a lamp with Teflon insulated wire which was used to heat the rabbits' ears to facilitate drawing blood samples. Five of the sixteen cage doors had been opened. Two of these cage doors could have been opened only by human hands because they had a special type fastener. The other three cages had large paper clip fasteners and the rabbits, in excitement, jumping against the cage doors could have forced them open. It is felt that the airmen were working in this area at the time of the fire as these doors were open and as the work tools carried in from the lock were adjacent to these open doors. It was also adjacent to the refuse that had been removed

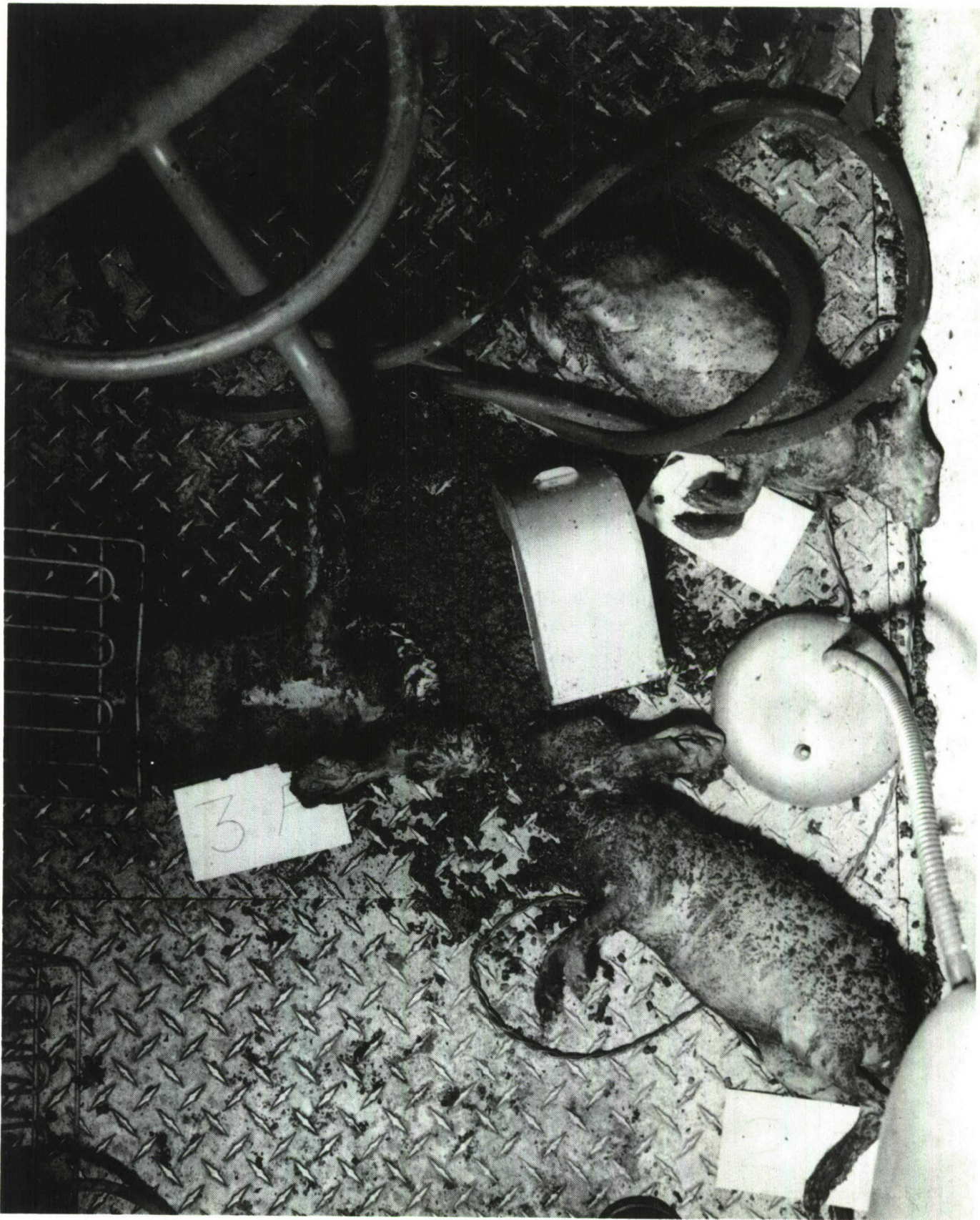


Figure 19 Right Side of Test Cell
28

from under some of the rabbit cages. We believe that one of the airmen accidentally stepped on the lamp cord, fractured the insulation and shorted it to the aluminum floor plate. Figure 20 is a picture of that cord and Figure 21 is a largely magnified view of the same cord showing bits of molten copper. There was a very noticeable electrical arc at that point. Figure 22 is another view of the same wire not quite so magnified but with the insulation stripped off. There is still another bit of molten material that was covered by the insulation. Laboratory experimentation was performed to try and confirm the fact that arcing could have caused a fire like this. Figure 23 shows the results of an electrical arc which had approximately one-tenth of a second duration. Figure 24 shows a wire which has experienced a one-half second arc. From these it appears that the arc on the wire in question lasted between one-tenth and one-half second. In none of these cases was the fuse that protected the circuit blown nor was the circuit breaker tripped. We calculated that there could have been at least 1300 joules of energy produced at this arc. Figure 25 depicts the non-skid aluminum floor plate. It is very difficult to see, but there is a residue and a small hole burned in the floor. Figure 26 is from the arcing experimentation that has been described. An analysis of the residue and the material inside the small burned area showed traces of copper and silver and some potassium, calcium and chloride. The wire was copper and silver.

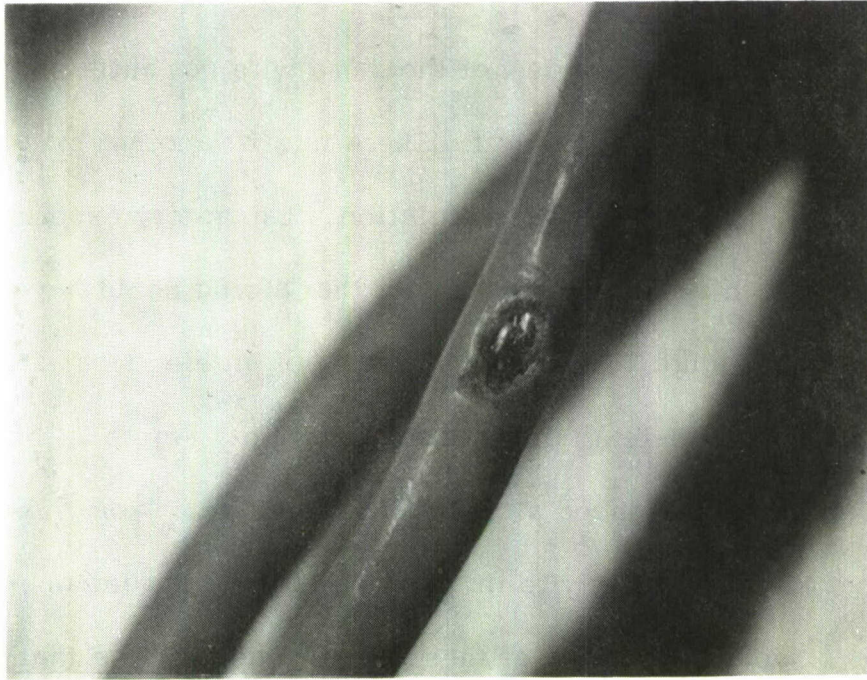


Figure 20 Lamp Cord with Abraded Teflon



Figure 21 Magnified View of Lamp Cord

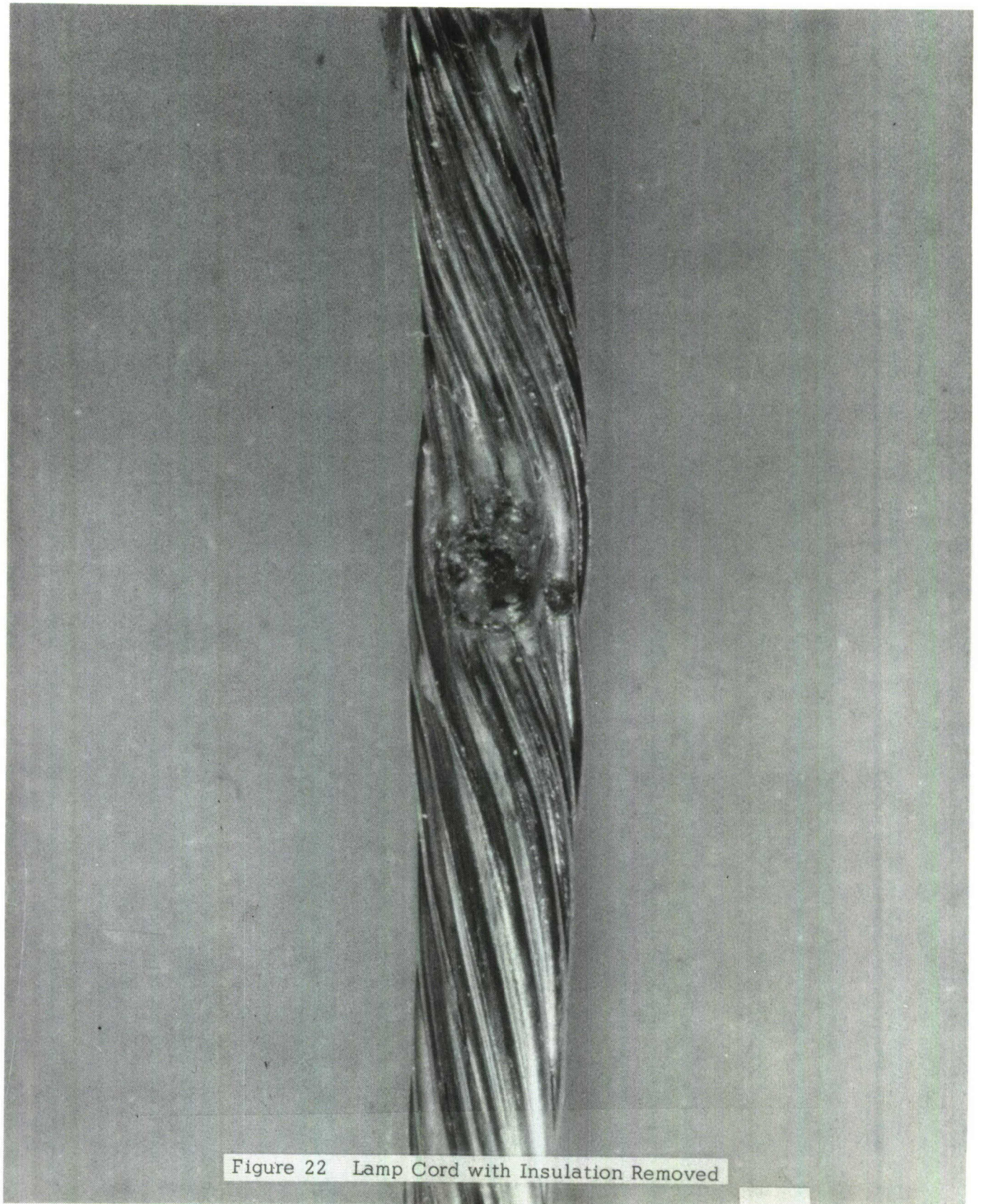


Figure 22 Lamp Cord with Insulation Removed

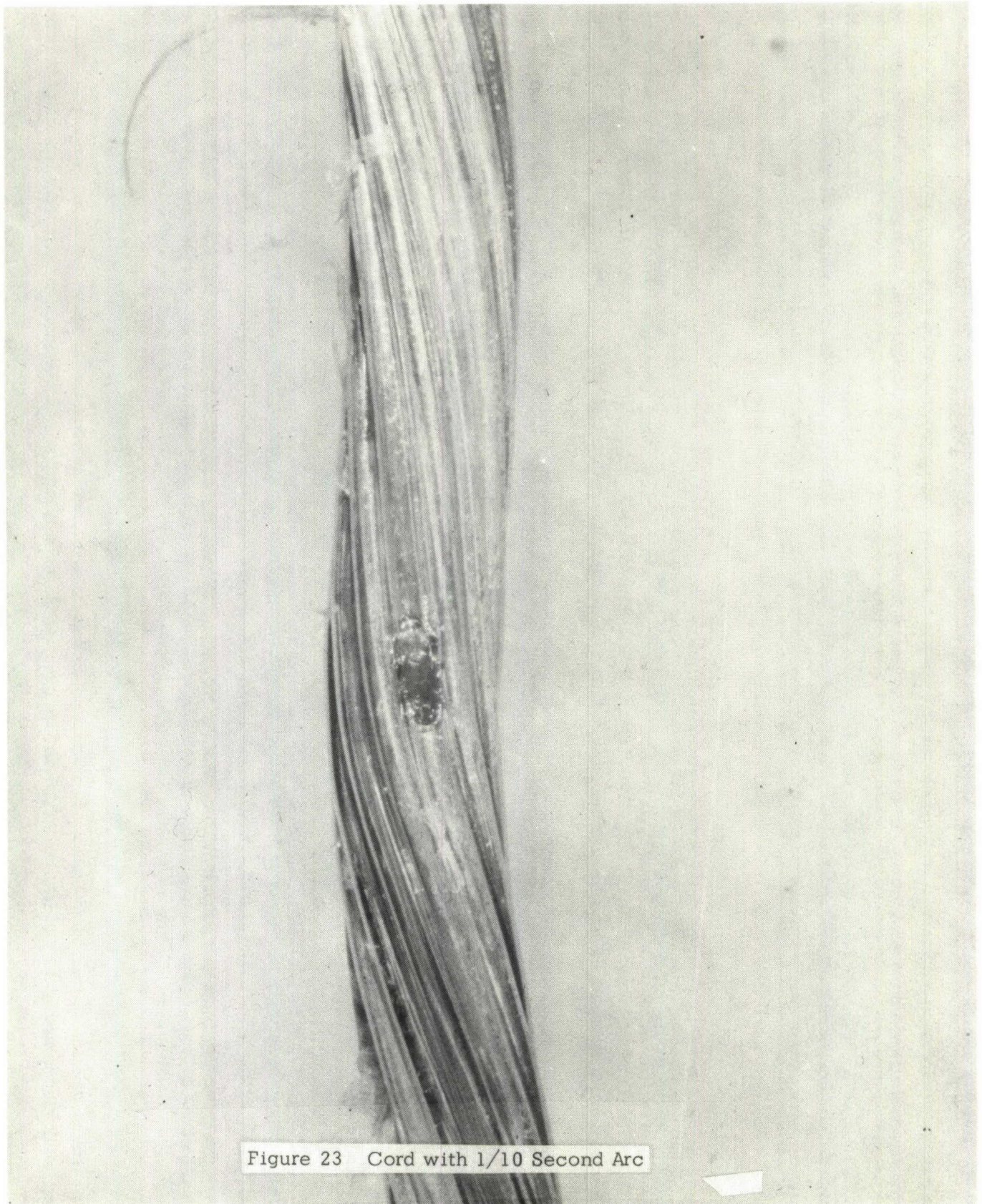


Figure 23 Cord with $1/10$ Second Arc

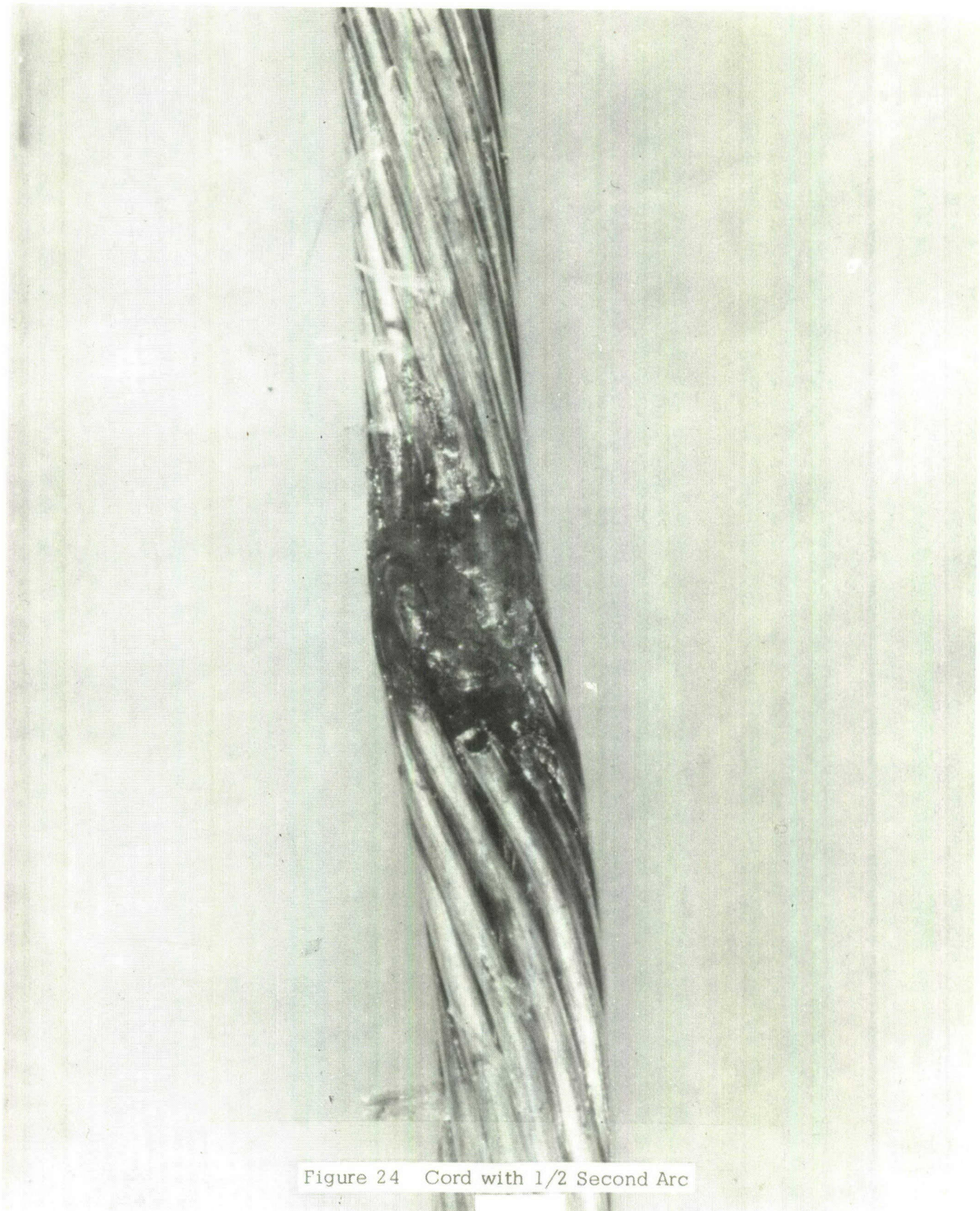


Figure 24 Cord with 1/2 Second Arc

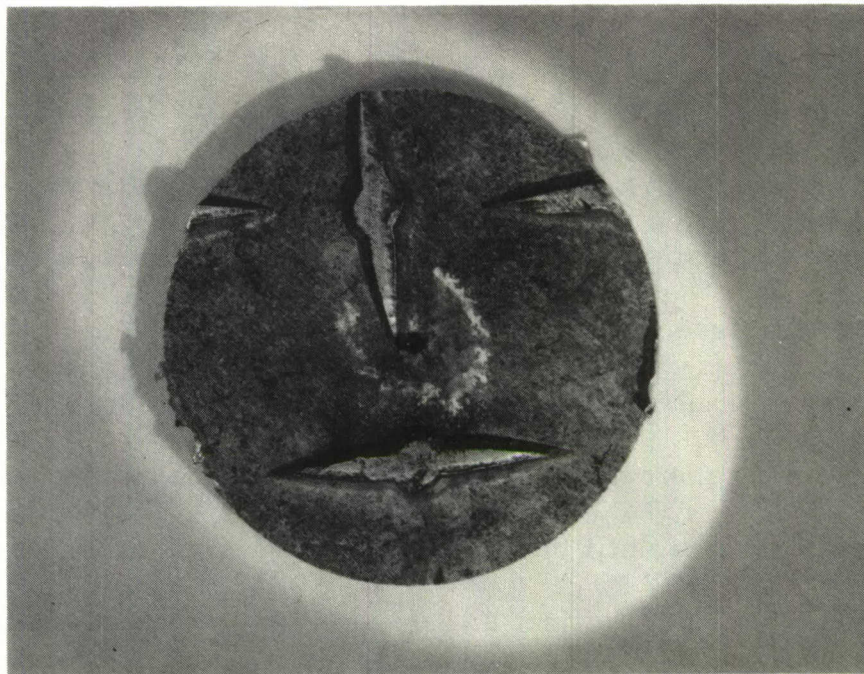


Figure 25 Burn Area in Floor Plate from Chamber

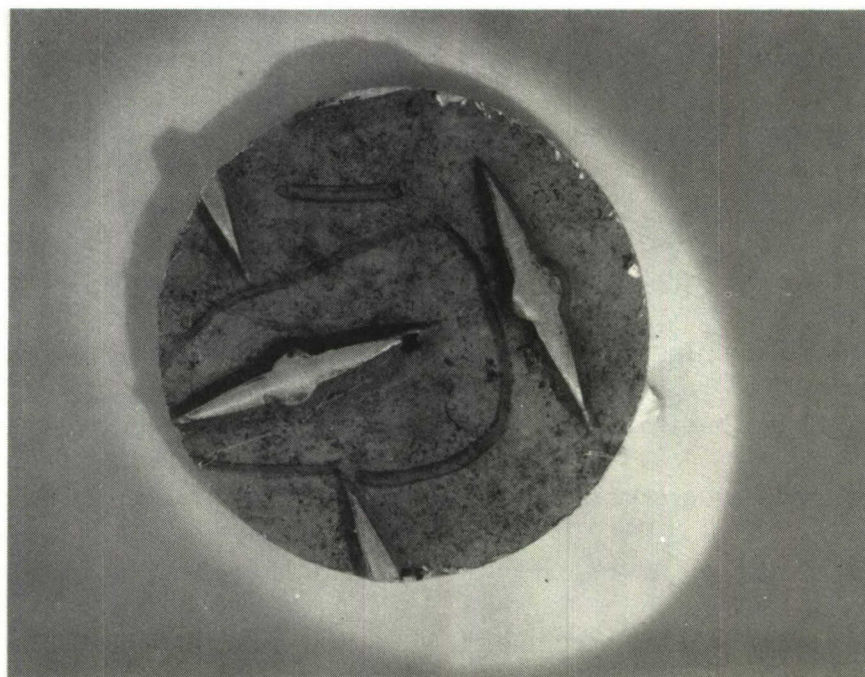


Figure 26 Burn Area in Floor Plate from Experiment

The heel on the boot or the wire insulation contributed the other materials. The analysis and the physical looks of the wire and floor plate in question and the wires and floor plate used in the laboratory are essentially identical.

Let me summarize. In reconstructing the events it is felt that this was a very short fire, that from the time of the first rumbling, so to speak, inside until the crew chief had declared the fire, summoned the medical officer and initiated the emergency dump valves, only eighteen seconds and perhaps as little as sixteen seconds elapsed. We believe that from the time the fire was first recognized outside (that is when the crew chief actually went around and saw the fire inside the chamber) until the emergency procedures had been performed, the chamber was back at ground level, two medical officers were on hand and the door was opened, between 31 to 33 seconds elapsed. The most probable cause of the fire was the electrical arcing from the Teflon insulated electrical wire. The other possible causes, a combustible atmosphere and the secondary fire in the air conditioning duct, have been discussed. As far as recommendations are concerned, they are rather specific. Maximum attempts should be made to remove flammable materials from this sort of experimental environment. Ignition sources should be minimized. Safety monitoring and procedures as well as maintenance,

monitoring and operating the facility need to be reviewed with regard to each particular experiment. There should be an automatic fire extinguishing system installed in chambers which use oxygen enriched atmospheres. The emergency and escape procedures should be reviewed and applied to each particular experiment. For example, when the base emergency response units--the dispensary, the fire department and the security police--may be expected to respond in case of an emergency, it is a joint responsibility for these agencies and the experimenters to keep each other informed. There was an extremely fast response to this particular fire by the fire department. The fire department was on the scene in two minutes from the time that the fire was first declared. The Director of Base Medical Services with his emergency medical equipment was also at the scene in slightly over two minutes, approximately two and a half minutes. There were two physicians available to give medical treatment immediately upon opening the chamber door.

There is a follow-on board which was established by our next higher headquarters, the Air Force Systems Command, which will keep most of the same group that investigated this accident in session so that the development of procedures, protective clothing, fire extinguishing and fire detection systems can be implemented and expedited. There has been a great deal of activity and we have

had active participation from our associates in the National Aeronautics and Space Administration. NASA has taken the lead in developing protective clothing. The Aerospace Medical Division has been carrying on some parallel developments and information has been exchanged on these items as well as on fire extinguishing systems.

This is, in summary, the results of the Accident Investigation Board.

FIRE PROTECTION FOR OXYGEN ENRICHED ATMOSPHERE APPLICATIONS

Mr B. P. Botteri
Fuels, Lubrication and Hazards Branch
Air Force Aero Propulsion Laboratory
Wright-Patterson Air Force Base Ohio

INTRODUCTION

The increased fire hazard in oxygen enriched atmospheres has been recognized in a qualitative sense for many years. (Ref 1, 2, 3). The recent Apollo and Two Man Space Environment Simulator fire tragedies have removed all speculation concerning the actual severity of the fire problem in these atmospheres. A concerted national effort has evolved to establish materials, methods and techniques to significantly minimize the likelihood of fire initiation and enhance the opportunity for personnel survival in the event of fire in future oxygen enriched atmosphere (OEA) applications (hypobaric and hyperbaric). The general approach to effective fire protection for OEA applications is no different from that normally followed in air. The essential factors include a strong emphasis on fire prevention supplemented as appropriate by fire detection and fire extinguishment and control capabilities. With regard to the normal terrestrial environment, although experience with the fire problem has been extensive, the achievement of effective fire protection in many instances is still inadequate as evidenced by the considerable fire losses and associated fatalities which are experienced each year. By

comparison, our experience with the fire problem in OEA is in its infancy and the depth of technical knowledge to yield a formula for effective fire protection is not as well established. It is the purpose of the discussion which follows to briefly review the effects of OEA's on fire initiation, propagation and extinguishment and to provide basic guidelines for achievement of effective fire protection. Specific factors which must be considered include the variable composition and pressure of OEA, the variety of combustible materials which may be encountered, the confined space (closed environment) conditions under which fires will occur, and the fact that these closed environments will be occupied by varying number of personnel.

FIRE INITIATION

Ignition Mechanisms - Flames involve strongly exothermic reactions between gases and vapors resulting in the generation of high temperature combustion products accompanied by light emission, under confinement, such as with oxygen enriched closed environment applications, the occurrence of flame can also result in sudden increases in pressure. Temperature, radiation and pressure are the criteria utilized to determine whether ignition has occurred. The initiation mechanisms involved in the flame reaction are complex and not too well understood. In general, if a fuel and oxygen molecule are to react, sufficient energy must be imparted to these molecules to enable a collision between the two to

result in a chemical transformation. For a particular reaction system the minimum energy which the molecules must possess to permit chemical interaction is normally referred to as the energy of activation. For many fuel-oxygen combinations at room temperature the activation energy is much greater than the average energy of the molecules. An increase in temperature increases the number of molecules in the activated state and the reaction rate increases. As the temperature is further increased, eventually enough fuel and oxygen molecules react and sufficient additional thermal energy is released to enable the combustion reaction to become self-sustaining until the one or the other, or both of the reactants have essentially been consumed. Regardless of whether the combustible material is a solid, liquid, or gas, initiation of the flame reaction occurs in the gas or vapor phase. Depending on the type of ignition source, the specific chemical nature and physical character of the combustible, and the composition and pressure of the atmosphere, the minimum initiation energy for flame will vary.

The initiation sources of principal concern for oxygen enriched atmosphere applications can be categorized into three types. These types include electrical sources such as electrostatic and break (arc) sparks; hot surfaces, such as friction sparks and heated wires; and heated gases, independent of surfaces generated by adiabatic

compression or jets of hot gas (includes pilot flames).

Effects of Atmosphere Composition and Environment Pressure and Temperature on Ignition Energy - The flame initiation energies for various combustibles (solids, liquids and gases) in environments of differing chemical composition, temperature and pressure are not amenable to calculation from existing scientific knowledge, but must be determined in each case by actual experimental evaluation. It is possible, however, to assess in a qualitative sense the effects of these environment parameters on the ignition energy requirements by typical electrical and thermal ignition sources. Figure 1, in an oversimplified manner, depicts the most likely effects of variations in oxygen concentration and pressure on ignition energy requirements. In general, at a given pressure the minimum ignition energy varies inversely with the change in the volume percent of oxygen. For a fixed volume percent oxygen content the minimum ignition varies inversely with the change in pressure. Depending on the particular combustible, there exists a minimum oxygen concentration and a minimum pressure below which ignition, from a practical standpoint, is not possible. An increase in environment temperature reduces the minimum electrical spark ignition energy requirements and enhances the possibility of auto-ignition. Typical minimum spark ignition energies for hydrocarbon fuels, combustible powders, and fabrics in 15 psia air and oxygen atmospheres are

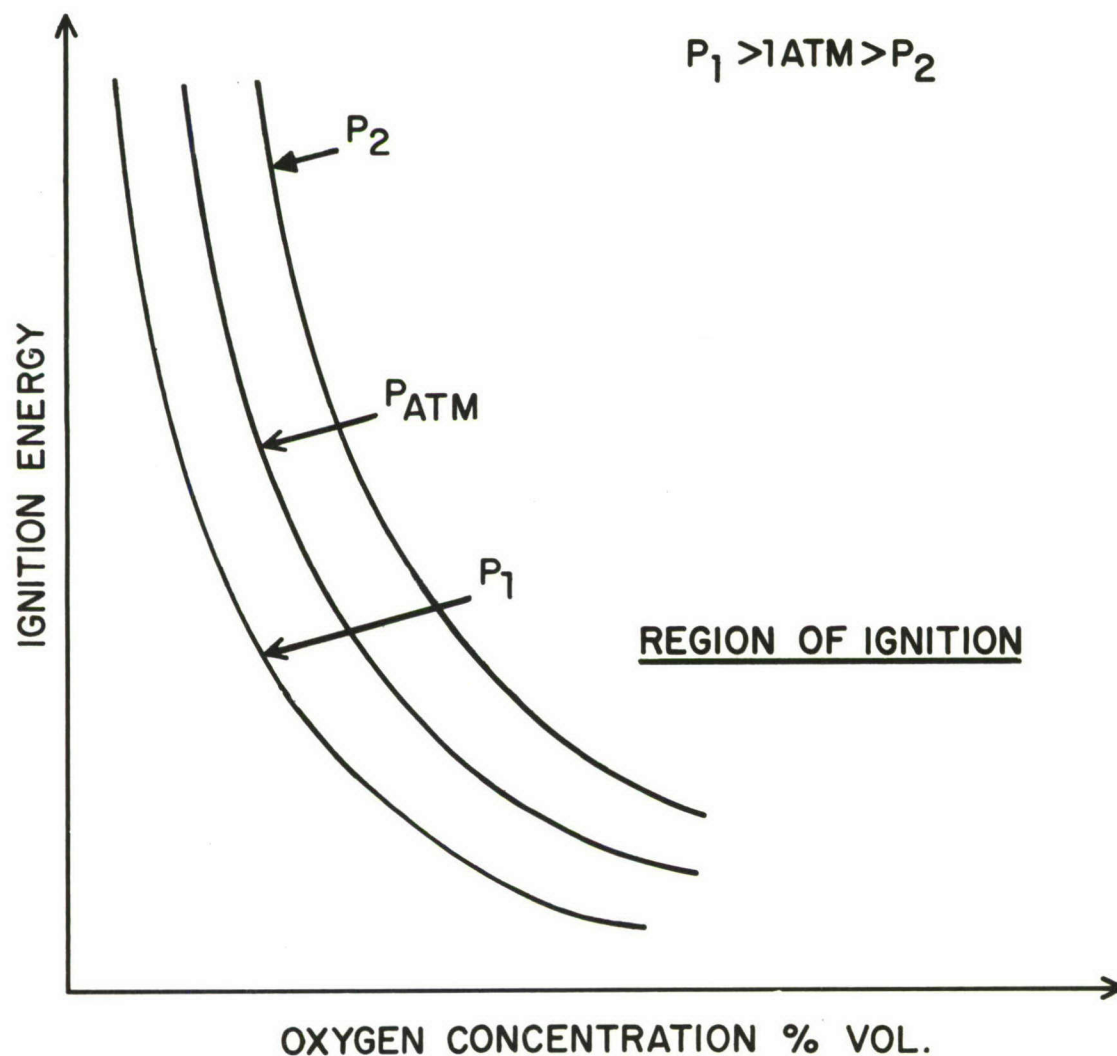


Fig.1 MINIMUM IGNITION ENERGY BEHAVIOR OF COMBUSTIBLES IN OXYGEN-DILUENT ATMOSPHERES AT DIFFERENT PRESSURES

indicated in Table I. There are a number of combustibles that do not adhere to the above ignition energy behavior patterns. It should be further noted that even for a given series of combustible atmosphere combinations there does not necessarily exist a regular pattern with respect to ease of flame initiation with different ignition sources. For example, a hydrocarbon-oxygen mixture is more susceptible to ignition by an electrical spark than the corresponding hydrocarbon-air mixture, but the two mixtures may exhibit the same autogenous ignition temperature when introduced into a heated vessel.

Effect of Inert Gas on Ignition - The likelihood of ignition of a combustible is primarily influenced by the oxygen content of the environment. An inert gas such as nitrogen or helium essentially provides a physical obstacle to the effective interaction of a fuel and oxygen molecule. For inert gases to have a pronounced effect on ignition energy they must be present in relatively high concentrations. If sufficient inert gas is added to the environment (adequate oxygen dilution), it is possible to render the atmosphere incapable of supporting combustion. Unfortunately, the addition of sufficient inert gas for this purpose would also result in an atmosphere which is not suitable for human survival and/or effective activity. The specific effect on ignition energy requirements by the typical ignition sources will vary with the particular inert gas selected. These effects in certain

TABLE 1

MINIMUM SPARK IGNITION ENERGY FOR VARIOUS
COMBUSTIBLES IN 15 PSIA AIR AND OXYGEN ATMOSPHERES

<u>COMBUSTIBLE</u>	<u>SPARK ENERGY, mj</u>	
	<u>AIR</u>	<u>OXYGEN</u>
Flammable Gas (Propane)	0.25	0.001
Powders (Dust)	10	-----
Fabric (Cotton)	800	800

instances correlate with the heat capacity and thermal conductivity properties of the different inert diluents.

Static Spark Generation by Personnel - The ignition of flammable gases and other combustible materials by static sparks generated by personnel under conditions prevailing in hospital operating rooms and oxygen tents has received considerable study by Guest and Plano (Ref 4, 5). The results of these investigations provide a good basis for assessing the likelihood of fire initiation by static sparks in other oxygen enriched atmospheres. Plano estimated maximum values of capacitance and potential likely to be encountered in oxygen tents as 100 micromicrofarads and 20 kilovolts respectively, with a resulting maximum spark energy of 20 millijoules. In Guest's survey of hospital operating rooms, charge potential or voltage observed on a single person engaged in various activities did not exceed 4 kilovolts, and the average capacitance in 22 tests was 204 micromicrofarads. This combination results in an electrostatic charge energy of 1.63 millijoules for the single person. The results of tests to evaluate the susceptibility of various fabric materials to ignition by single sparks and repetitive sparking of various energy in air and 100% oxygen are summarized in Table 2. In general, static sparks likely to be generated by personnel can possess sufficient energy to ignite combustible gases and powders in air as well as 100% oxygen. These sparks, however,

TABLE 2

SPARK IGNITION OF COMBUSTIBLE MATERIALS IN OXYGEN ENRICHED

ATMOSPHERES (N₂ and O₂ @ 1 ATM)

(REFERENCE: PLANO AND GUEST)

COMBUSTIBLE	THICKNESS (IN.)	SINGLE SPARK			REPETITIVE SPARKS		
		20 mj Oxygen (Vol%)	800 mj Oxygen (Vol%)	← NI →	← NI →	90 mj-60 SPS Oxygen (Vol%)	20 mj-30 SPM Oxygen (Vol%)
Vinyl Plastic	0.002	21 60 100	21 60 100	← NI →	← NI →	21 100	52-64 100
Tissue Paper	0.0025	"	"	"	"	NI (1800) 5	
Nylon	0.006	"	"	"	"	" 10	
Wool	0.022	"	"	"	"	" 30	
Cotton Muslin	0.012	"	"	"	"	" 5	
Dacron - Cotton	0.008	"	"	"	"	" 100	
Absorbant Cotton	Tufts	"	"	"	"	" 100	
Absorbant Cotton Fiber and 5.1 wt % Petrolatum	Tufts	"	"	"	"	NI (4000) 8 (2800)	
						15 (1300)	

NI = No Ignition SPS and SPM = Sparks per Second and Minute, Respectively

provide a very low probability for ignition of solid materials such as cotton and nylon. Appropriate procedures should be followed, nevertheless, to minimize the likelihood of static spark generation from personnel and equipment.

COMBUSTION

Combustion Mechanisms - Combustion is a chemical reaction between a fuel and an oxidant. The velocity of a chemical reaction is often called the reaction rate. As with other types of chemical reactions, the rapidity (reaction rate) of the combustion process is dependent on the chemical nature and physical character of the fuel and oxidant, their relative concentration, pressure and temperature, and other physical parameters such as chamber configuration and ventilation. The combustion processes involved with various types of fuel with air and other oxygen enriched atmospheres is a complex and extensive subject the comprehensive discussion of which is beyond the scope of this report. However, it is important to review the essential fundamental features of the combustion process to obtain a better appreciation of the fire hazard problem under various oxygen enriched atmospheres, closed environment applications. For this purpose the various combustible materials of concern can be divided into two principal categories, the first consisting of combustible liquids, vapors and gases and the second all combustible solids.

Combustible Gases, Vapors and Liquids - In the discussion of ignition mechanisms it was indicated that for ignition to be possible an adequate fuel concentration must be available in the particular oxidizing atmosphere. Once ignition does occur, the sustainment of combustion requires a continued supply of fuel and oxidant. In the case of combustible gases, vapors and liquids two general types of mixing, homogeneous or heterogeneous, can occur within the atmosphere.

a. Homogeneous Systems - A homogeneous mixture is one in which the combustible and oxidant are intimately and uniformly combined so that any small volume sample of the environment is truly representative of the remainder of the environment. In the case of oxygen enriched atmospheres, homogeneous mixtures are only possible with combustible gases and vapors. A flammable, homogeneous mixture is one whose composition lies between the limits of flammability of the combustible gas or vapor in the particular atmosphere at a specified temperature and pressure. The limits of flammability represent the extreme concentration limits of a combustible in an oxidant through which a flame, once initiated, will continue to propagate at the specified temperature and pressure. For example, hydrogen-air mixtures will propagate flame between 4.0 and 74 volume percent hydrogen at 70°F and atmospheric pressure. The smaller value is the lower (lean) limit and the larger

value is the upper (rich) limit of flammability.

When the mixture temperature is increased the flammability range widens (See Figure 2). A decrease in temperature can result in a previously flammable mixture becoming nonflammable by placing it either above or below the limits of flammability for the specific environment conditions; a reduction of temperature can also result in condensation of fuel and thereby altering the flammability picture. It will be noted in Figure 2 that a minimum temperature exists for each fuel below which sufficient vapor is not released to form a flammable vapor-air mixture at the specific environment pressure. This minimum temperature is referred to as the Flash Point. The Flash Point temperature for a combustible varies directly with environment pressure.

An increase in atmosphere oxygen concentration also widens the flammability range, the upper limit being affected much more than the lower limit. For example, in a 100% oxygen atmosphere at 70°F and 14.7 psia, the upper limit for hydrogen increases to 95 volume percent compared to 74 percent in air while the lean limit remains essentially the same. A reduction in atmosphere oxygen concentration results in a narrowing of the flammability range until at a certain oxygen concentration the limits merge and flame propagation is no longer possible. Reduction of the oxygen content below this minimum value is one means of effecting fire control. In practice carbon dioxide or nitrogen are utilized for this

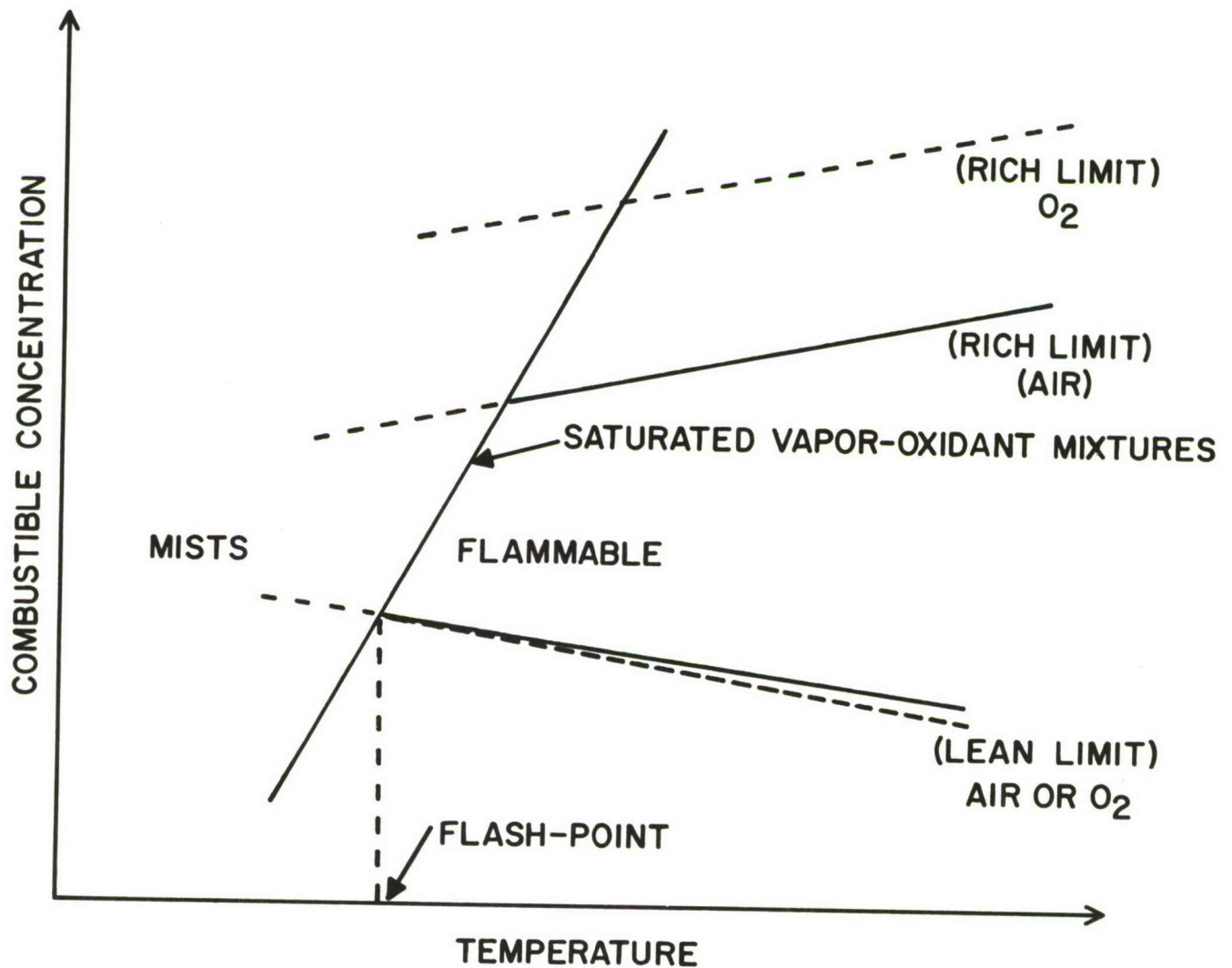


Fig.2 EFFECTS OF TEMPERATURE ON THE LIMITS OF FLAMMABILITY OF A COMBUSTIBLE VAPOR IN AIR AND OXYGEN (AFTER VAN DOLAH, ET AL)

purpose. The extent of oxygen dilution varies with the particular diluent gas selected.

Total environment pressure also has an effect on the limits of flammability. An increase in pressure broadens the flammability range, the rich limit being influenced more than the lean limit. For example the flammability limits for natural gas-air mixtures at 500 psig are 4.45 and 44.20 volume percent compared to 4.50 and 14.20 volume percent at normal atmospheric pressure. A decrease in environment pressure below 14.7 psia produces little effect on the limits of flammability until the low pressure limit is reached. The low pressure limit is dependent on the particular fuel and oxidant as well as the size, geometry and attitude of the confining vessel. A flammable mixture will propagate through a cylindrical vessel only if the diameter of the vessel is greater than the quenching (low pressure) limit for the mixture at the particular pressure. As the pressure is reduced the size of the vessel must be increased. The quenching limit for a hydrocarbon-air mixture at room temperature and atmospheric pressure is approximately 0.1 inches, compared to approximately 1 inch at 1 psia. The oxygen content of the environment has a significant effect on the quenching limit. For example, the quenching distance for hydrocarbon-oxygen mixtures at atmospheric pressure is approximately 0.01 inches or one-tenth that of hydrocarbon-air mixtures. The quenching distances

exhibited by different fuel-oxidant mixtures are utilized in the design of flame arresters. The design of effective flame arresters for oxygen enriched atmosphere applications is very difficult because of the very small quenching distances involved.

b. Heterogeneous Combustible-Oxidant Systems - Under practical application conditions the fire problem usually involves heterogeneous rather than homogeneous combustible-oxidant mixtures. The heterogeneity can include single as well as multiphase systems. The first pertains to gaseous fuel-oxidant mixtures and is heterogeneous in view of the concentration gradients which normally exist when the combustible vapor is first introduced into the oxidizing atmosphere. The second type of heterogeneous system is formed when a liquid fuel is injected into the oxygen containing atmosphere. These systems are also illustrated in Figure 2. In the case of the single phase heterogeneous system, both flammable and nonflammable mixtures are formed at temperatures above the Flash Point. The flammable zones exhibit ignition and burning characteristics similar to flammable homogeneous mixtures. Flammable heterogeneous vapor-mist-oxidant mixtures can be formed at temperatures below the Flash Point; flammable sprays can be produced over a wide temperature range both below and above the Flash Point. Ignition of a flammable mist or spray requires vaporization of the fuel droplets to form flammable heterogeneous single phase mixtures; as a result the

ignition energies for these mixtures are higher than those of flammable single phase mixtures.

For most practical cases, the type of flame which is encountered is referred to as a diffusion flame and requires the diffusion of both oxidant and fuel to the flame front. Diffusion flames represent a special case of flame propagation in heterogeneous systems. The rate of burning is primarily dependent on the rate at which the fuel and oxidant are brought together. Increasing the oxidant content such as in oxygen enriched atmosphere applications results in a significant increase in burning rate.

Combustible Solids - Once a particular solid combustible has been ignited, propagation of flame requires that a portion of the heat of combustion be fed back to the solid fuel to cause its vaporization and/or pyrolysis thereby making additional gaseous fuel available to mix with the oxidant. The flame process is of the diffusion type. Although flammable dust-oxidant and combustible gas-oxidant mixtures are experienced in normal terrestrial earth atmosphere environments, it is assumed that extra special precautions will be taken to preclude even the remote possibility of combustible dust or gas mixtures ever existing in closed environment applications. Accordingly, the fire hazard in the latter type applications will, to a large extent, be associated with common materials such as those utilized in garments, bedding and electrical

wiring. In oxygen enriched atmospheres man must also be considered a combustible. Although it is not possible to predict the burning behavior of a given material in atmospheres of different composition and pressure without actual experimentation, the general effects of these parameters on flame propagation is amenable to qualitative discussion. The rate of flame propagation over the surface of a solid combustible, referred to as the Flame Spread Rate is a property used to evaluate the fire hazard in different oxygen enriched atmospheres. The observed effects of atmosphere composition and pressure on this fire property is illustrated in Figure 3. In general, increasing the partial pressure of oxygen can change the classification of a material from the nonflammable to the flammable category. For materials in the flammable category, further increase in the oxygen partial pressure results in a higher flame spread rate. The specific diluent gas utilized also influences the flame spread rate. For example, the flame spread rate for a given material in a particular helium-oxygen atmosphere is greater than that in a corresponding nitrogen-oxygen atmosphere because of the higher thermal conductivity of helium.

Effects of Fire in Oxygen Enriched Atmospheres - Thus far we have seen that compared to the normal air atmosphere, oxygen enriched atmospheres facilitate the initiation of the combustion process and once ignition has occurred, the flame reaction proceeds with greater rapidity.

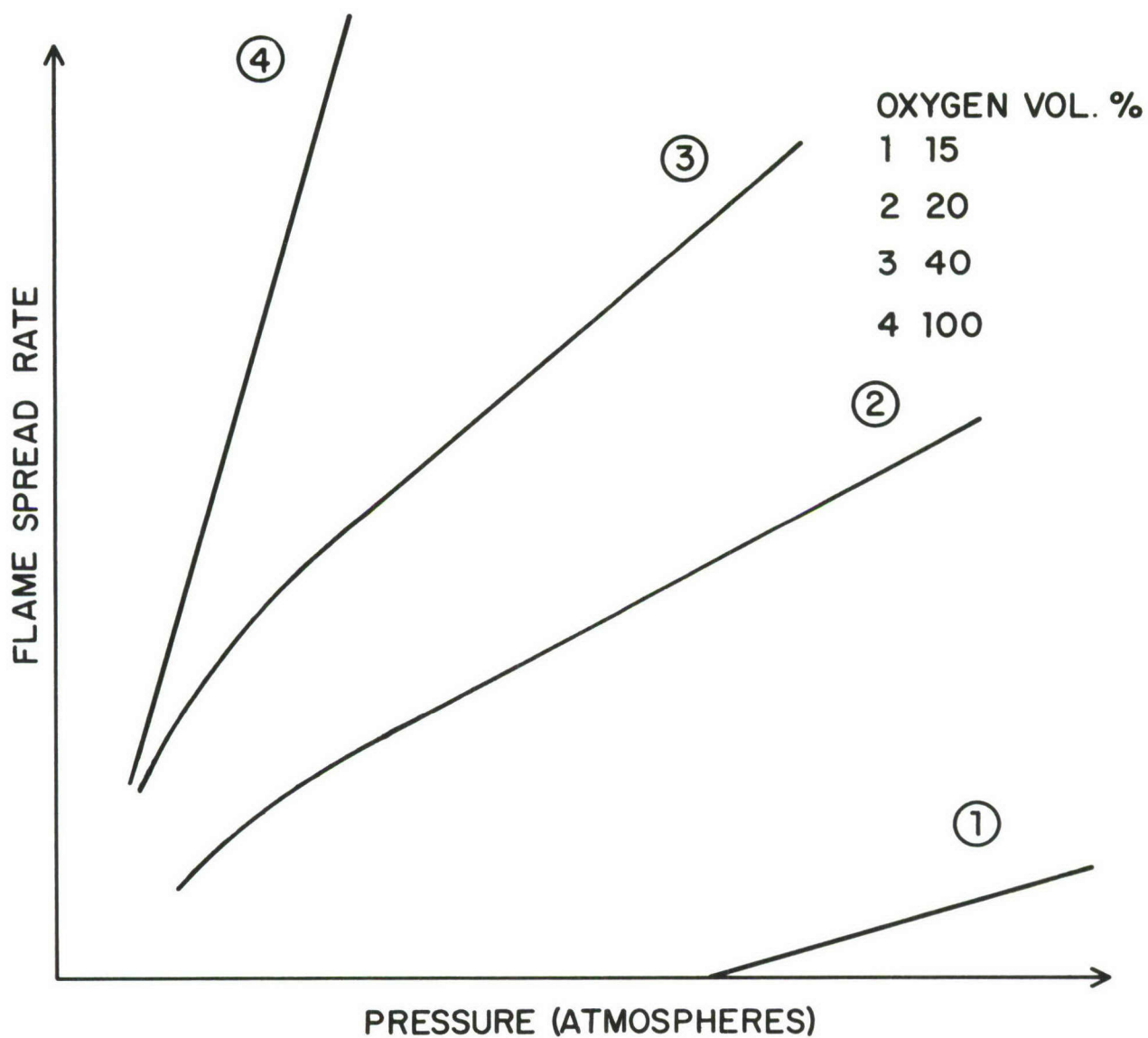


Fig.3 EFFECTS OF ATMOSPHERE OXYGEN CONTENT AND ENVIRONMENT PRESSURE ON FLAME SPREAD RATE

Another important consideration in the analysis of the overall fire problem is the fact that oxygen enriched atmospheres will primarily be confronted under closed environment (fixed volume) conditions such as in hypobaric and hyperbaric chambers. As a consequence, the combustion of a relatively small quantity of solid combustible can result in the rapid generation of extremely high temperatures and increased pressure. The high temperature may also result in the spontaneous ignition of other combustibles some distance from the initial reaction zone thereby contributing to the rapid spread of the fire. The high temperatures and toxic combustion products which are generated are in themselves potentially lethal to any personnel in the environment even if these personnel are not themselves engulfed in flames. The increased pressure produced in association with the flame process can also result in the explosive rupture of the chamber.

The effects of oxygen content and pressure on the quantity of fuel which can be consumed and the resulting maximum theoretical temperatures and pressures that can be attained in air and several other typical oxygen enriched atmospheres in a 360 cubic feet chamber are indicated in Table 3. The maximum temperatures and pressures in this Table are recognized to be much higher than those that would be experienced under true closed environment fire conditions. The specific values listed were calculated with the assumptions that (1) combustion of the fuel is instantaneous,

TABLE 3

OXYGEN CONTENT, MAXIMUM FUEL CONSUMPTION AND RESULTING COMBUSTION TEMPERATURES AND PRESSURES IN DIFFERENT ATMOSPHERES IN 360 CU FT VOLUME

FUEL ATMOSPHERE	CELLULOSE				HYDROCARBON			
	5 psia (100% O ₂)	15 psia (Air)	15 psia (100% O ₂)	45 psia (Air)	5 psia (100% O ₂)	15 psia (Air)	15 psia (100% O ₂)	45 psia (Air)
Oxygen Content (lbs)	10.6	6.4	32.0	19.2	10.6	6.4	32.0	19.2
Maximum Burnable Fuel (lbs)*	8	2.7	24	8.1	2.38	0.8	7.2	2.4
Heat of Combustion BTU/lb	7200				21000			
Maximum Heat Release (BTU/lb x lbs fuel)	57,600	19,540	172,800	58,320	49,980	16,800	151,200	50,400
Maximum Theoretical Flame Temperature (°R) **	10,700	3,750	10,700	3,750	11,000	3,000	11,000	3,000
Maximum Pressure Ratio (Pfinal/Pinitial)	36	8	36	8	33	7	33	7
Maximum Final Pressure (psia)	180	120	540	360	165	105	495	315

*Assumes all but 10 volume percent of available O₂ can react.

**Does not consider dissociation of product gases.

(2) none of the heat generated is lost to the walls of the chamber, and
(3) no dissociation of the product gases occurs. Solid combustibles such as fabric materials burn rapidly in 100% oxygen but consumption of the stoichiometric amount of material would require several seconds, allowing a considerable fraction of the thermal energy generated to be absorbed by the walls.

Experiments were recently conducted by this laboratory to evaluate the pressure rise associated with the combustion of cotton coverall material in a 1.6 cubic foot explosion test chamber. Tests were conducted in 100% oxygen at different pressures with stoichiometric fuel loading and a geometrical arrangement likely to maximize the flame spread rate. Several seconds after ignition peak pressures corresponding to approximately 20% of the theoretical maximum pressure rise indicated for cellulose in Table 3 were obtained.

Figure 4 depicts the typical pressure profiles associated with the combustion of stoichiometric hydrocarbon gas mixtures in air and oxygen compared to that observed with cotton under closed vessel conditions. Under appropriate vessel length/diameter ratios ignition of hydrocarbon-oxygen gas mixtures can result in detonation and considerably higher peak pressures. The combustion pressure profile exhibited by cotton is very likely typical of that which was experienced in the Apollo fire and resulted in rupture of the capsule.

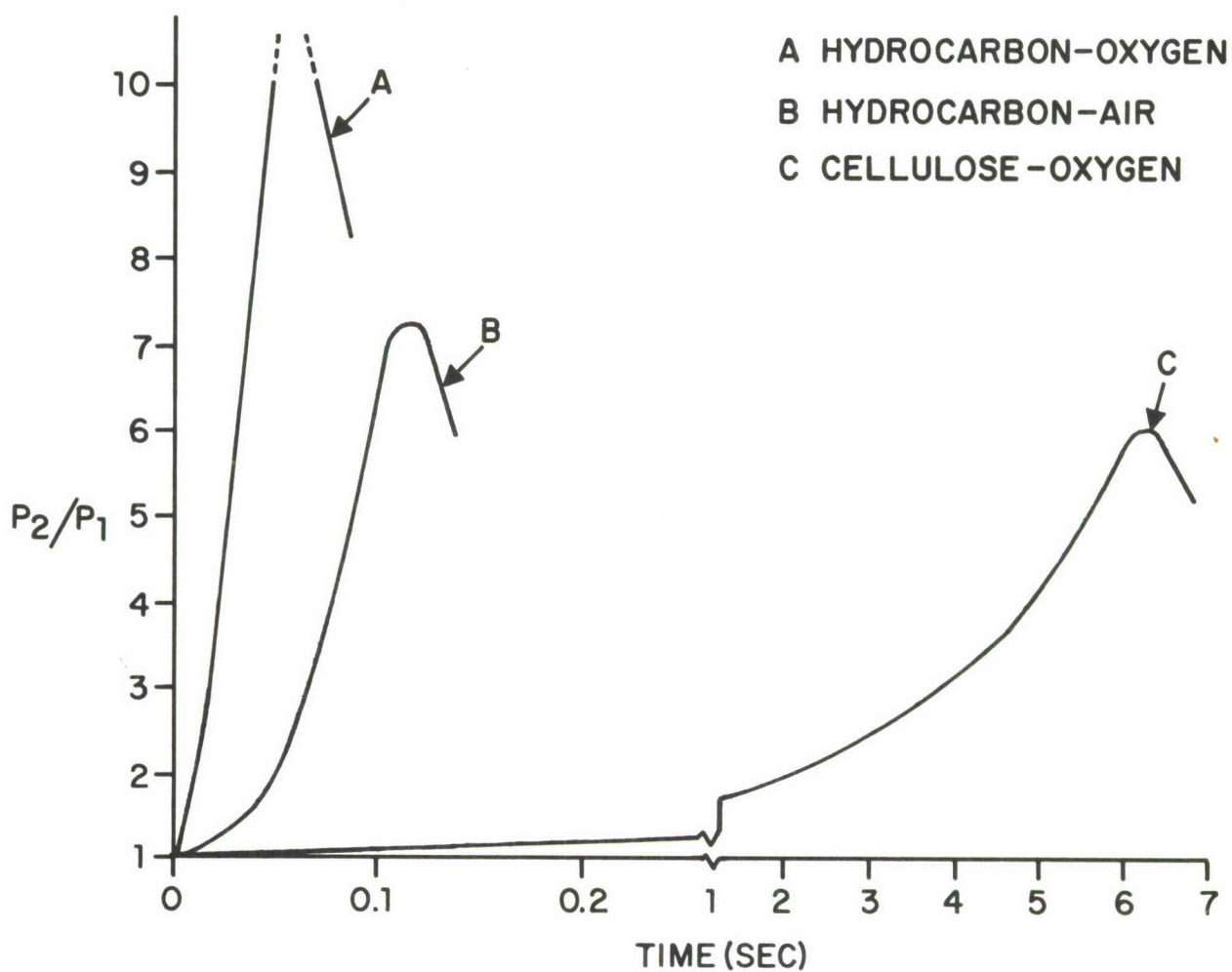


Fig.4 TYPICAL PRESSURE PROFILES FOLLOWING IGNITION OF GASEOUS HYDROCARBON AND CELLULOSE TYPE FUELS IN AIR AND OXYGEN IN CLOSED VESSELS

FIRE DETECTION

Because of the rapidity of fire development in oxygen enriched atmospheres and the consequent extreme hazard to personnel, it is essential that reliable detection techniques capable of initiating meaningful fire extinguishment or other emergency action be adopted as a mandatory protection requirement. Detectors for this application should provide volume surveillance and permit early and rapid detection of incipient combustion as well as flame. Table 4 indicates the various types of detectors currently available for industrial and military aircraft fire protection. In general, these detectors rely upon either the temperature rise, radiation emission or combustion products associated with the flame process for activation. Certain of these detectors such as the overheat or rate of temperature rise detectors are not acceptable for this OEA application because of their inherent slow response time and limited volume coverage. Flame radiation (UV and IR) sensors and smoke detectors in combination appear to be ideally suited for this application.

FIRE EXTINGUISHMENT AND CONTROL

Although stringent requirements must be imposed to limit the type, quantity, and placement of materials used in oxygen enriched atmospheres to minimize the likelihood of fire occurrence, it will be virtually impossible to eliminate all combustible materials. Accordingly, strong

TABLE 4

AVAILABLE TEST CHAMBER FIRE DETECTION SYSTEMS

TYPE OF SYSTEM	SPECIFIC TO FIRE OR IGNITION	APPROXIMATE RESPONSE TIMES	APPLICABILITY	VOLUME COVERAGE
SMOKE DETECTORS LARGE PARTICLES (1)	No	2-5	No	Yes
SMOKE DETECTORS SMALL PARTICLES (1)	No	2-5	No	Yes
INFRARED SOLID STATE DETECTORS	Yes (2)	0.1 (2)	Yes	Yes
THERMOCOUPLES	No	.05	No	No
CONTINUOUS ELEMENT OVERHEAT DETECTORS	No	5	No	No
EUTECTIC ALLOY TYPE	No	5	No	No
ULTRAVIOLET DETECTORS	Yes	0.010	Yes	Yes

(1) Excellent for incipient fire detection.

(2) Specificity, fast response and sensitivity are not available in one system.

consideration must be given to the inclusion of an effective fire extinguishment capability for additional protection of personnel. The incorporation of suitable fire extinguishing systems in ground facilities would not entail any limitations in the use of these facilities for their original intended purpose. In the case of space vehicle systems, however, where weight is a very serious consideration, the incorporation of a fire extinguishing system may not be so easily tolerated.

General Theory of Fire Extinguishment - Fire extinguishment is accomplished by physical or a combination of physical and chemical actions. These actions involve four basic types of mechanisms. First the combustible material can be cooled to a temperature below that required for ignition or the evolution of flammable vapors. The second mechanism involves smothering the fire by reducing the oxygen or fuel concentration to a level that will not support combustion. A third mechanism involves the separating of fuel from oxidizer either by removing one or by mechanically separating the two. This is the major mechanism of mechanical protein foam on jet fuel fires and is often referred to as "blanketing" action. The final mechanism involves chemical interference or inhibition of the reactions occurring in the flame front or just before the flame front.

Fire Extinguishing System Selection Criteria for USAF OEA Chamber Applications - The incorporation of an effective fire extinguishing system

capability in Air Force OEA chambers was considered to be an essential requirement for meaningful personnel protection in future chamber operations. Stringent procedures will be implemented to preclude the existence of flammable liquids, gases and dusts in the chamber environment. Accordingly, the following initial criteria were utilized for immediate system selection for full-scale fire test evaluations:

- a. The fire extinguishing agent must be effective on Class "A" fires (solid materials) in OEA with principal emphasis on protection of personnel.
- b. The extinguishing agent should provide a minimum toxic hazard.
- c. The system should incorporate an essentially instantaneous fire detection capability and provide for sufficient agent discharge through the chamber volume in less than 2 seconds.
- d. The fire extinguishing system should be state-of-the-art to permit immediate incorporation in OEA chambers.

It was further recognized that longer term research on fire extinguishing agents and overall system design may be required to yield improved extinguishing systems for OEA applications.

Selection of Extinguishing Agents - A number of different types of extinguishing agents were considered for use in OEA. These agents are indicated in Table 5. Agents such as nitrogen and carbon dioxide which depend primarily on the dilution of the oxygen content to a level which

TABLE 5

CANDIDATE FIRE EXTINGUISHING AGENTS FOR OEA

<u>AGENT</u>	<u>MODE OF ACTION</u>	<u>COMPATIBILITY</u>	
		<u>PERSONNEL</u>	<u>O₂ - FIRES</u>
Water	1, 2, 5	Excellent	Good
Foam	1, 3, 5	Good	Unknown
Dry Chemical (NaHCO ₃ , ABC)	3, 4, 5	Good	Unknown
CO ₂	1, 2	Fair	Poor
N ₂	2	Poor (Anoxia)	Poor
CF ₃ Br	1, 2, 4	Good	Very Good

MODE OF ACTION

1. Quenching (Cooling)
2. Inerting (O₂ - Dilution)
3. Blanketing
4. Chemical Inhibition
5. Radiation Shielding

no longer will support combustion were eliminated from consideration for 100 percent oxygen applications because of poor effectiveness. This is shown in Figure 5.

Although foam type extinguishing agents may eventually offer promise for chamber application, their effectiveness on Class A fires in OEA had not been established and their immediate availability in an extinguishing system capable of meeting the desired reaction time was questionable.

Dry chemical extinguishing agents were also considered. The effectiveness of these agents in 100% oxygen was not established. Although these agents should provide rapid suppression of flame and excellent radiation shielding when initially discharged, the permanency of the fire extinguishment action was doubtful.

Accordingly, water and CF_3Br were selected for immediate evaluation. The effectiveness of water had been demonstrated for OEA in studies conducted by the RAF Institute of Aviation Medicine and systems meeting the desired performance goals were state-of-the-art. CF_3Br was also known to be effective for Class "A" fires in 100% oxygen if discharged in sufficient quantity. The agent in the unpyrolyzed condition is relatively nontoxic. It was further considered that the use of CF_3Br in an extinguishing system providing for automatic, rapid and adequate agent discharge at the initial indication of fire would

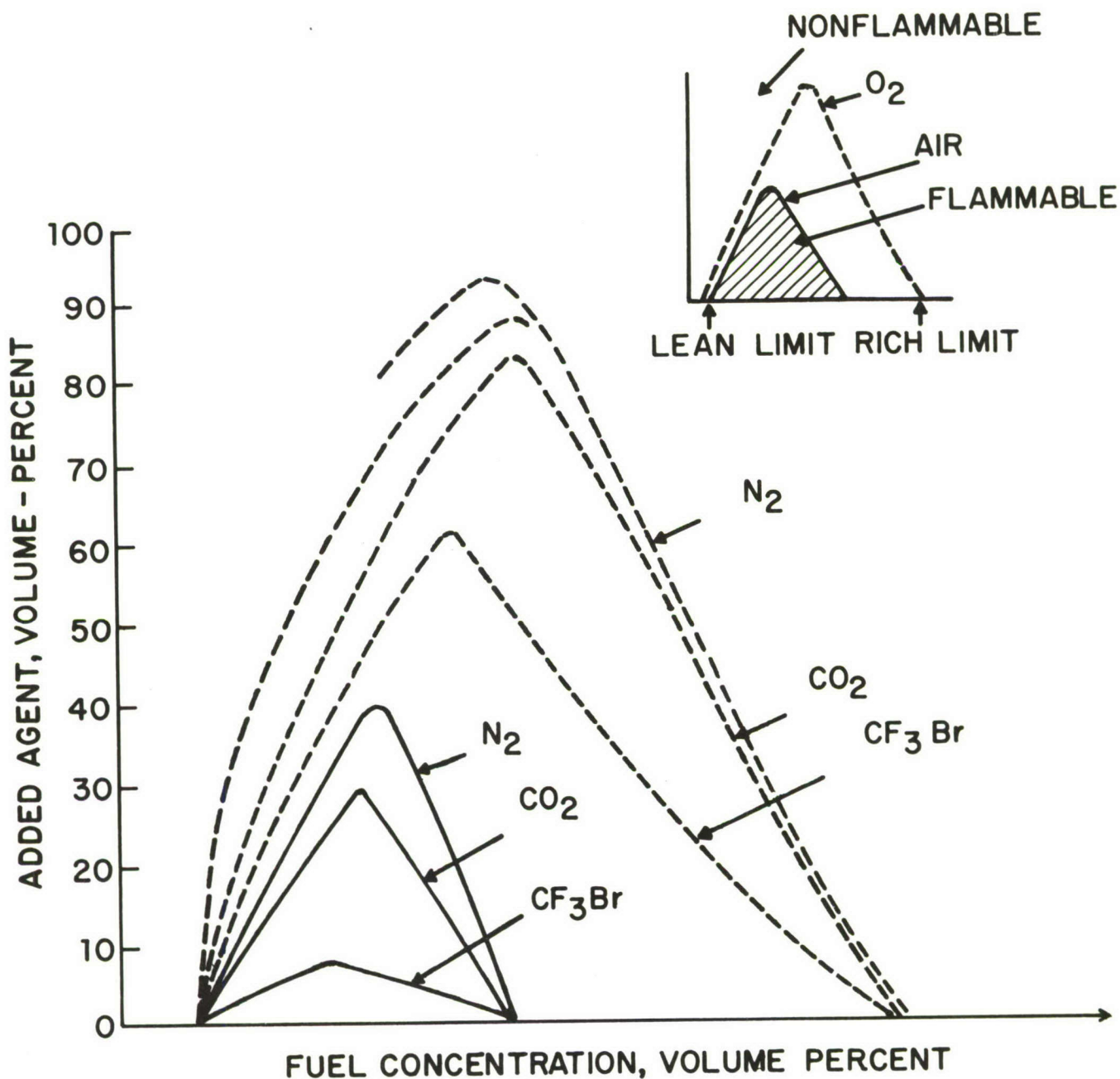


Fig.5 LIMITS OF FLAMMABILITY OF VARIOUS HYDROCARBON FUEL-OXIDANT-AGENT MIXTURES (%AIR OR OXYGEN= 100%- %FUEL - %AGENT)

limit any agent pyrolysis to a level which would be tolerable for personnel. Extinguishing systems utilizing this agent are also state-of-the-art.

Discussion of the toxicity of CF_3Br and the results of full-scale fire tests in OEA with the water and CF_3Br fire extinguishing systems will be covered in other papers at this conference.

SUMMARY AND CONCLUSIONS

Effective fire protection is achievable in oxygen enriched atmospheres. Specific requirements toward the realization of this goal include:

- a. Elimination of ignition sources.
- b. Minimization of combustibles with the complete exclusion of flammable liquids and gases.
- c. If combustible materials must be employed, the type, quantity and arrangement in the chambers must be carefully controlled.
- d. Fire walls and other containment techniques should be utilized to isolate potential high risk fire zones.
- e. A fixed fire extinguishing system should be utilized which incorporates automatic initiation by flame and smoke detectors as well as manual initiation and provides rapid (< 2 seconds) and sufficient agent discharge.

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FIRE EXTINGUISHMENT AND PROTECTIVE CLOTHING EVALUATIONS

Captain Donald I. Carter
Bioenvironmental Engineer
Directorate of Research & Development
Aerospace Medical Division
Brooks Air Force Base Texas

This paper will describe the work which the Aerospace Medical Division has accomplished in fire extinguishment and protective clothing subsequent to the fire in the Two Man Space Environment Simulator at Brooks AFB on 31 January 1967. The basic objective of this work was to evaluate "off-the-shelf" equipment which, if it performed satisfactorily, could be installed in existing chambers to minimize the amount of time the chambers would be out of commission. It is recognized that further development work should be done to evolve more effective protective clothing and fire extinguishing systems. This paper will be divided into three sections--fire extinguishment in a hypobaric environment, fire extinguishment in a hyperbaric environment, and protective clothing evaluations.

Fire Extinguishment in a Hypobaric Environment

Subsequent to completion of the studies which Mr Botteri has described, systems were fabricated to test the two extinguishing agents which showed the most potential, i.e., water and Freon 1301 (CF_3Br). The objectives were to (1) determine the relative effectiveness of ultraviolet, infrared, and various smoke detectors; (2) ascertain

the relative advantages and disadvantages of water and Freon 1301 as extinguishing agents in oxygen enriched atmospheres; and (3) assure that the sensing systems and the extinguishing systems could be integrated with an electronic firing circuit to provide reliable functioning in these atmospheres.

The chamber used in these investigations was the same chamber in which the fire occurred at Brooks AFB on 31 January. It is elliptical in shape, 2.4 meters by 1.5 meters (8 ft x 5 ft) on its major and minor axes, with a floor plate approximately 0.6 meters (2 ft) from the bottom of the major axis and divided into two cells--an air lock 1.8 meters (6 ft) in length and the main test cell 3.7 meters (12 ft) in length. The extinguishing tests were accomplished in the larger of the two cells. See Figure 1.

The environment within the chamber for these tests was greater than 98% oxygen at 258, 380 and 600 mm Hg for a total of three tests of the Freon 1301 extinguishing system and a total of three tests of the water extinguishing system. (See Figures 2 and 3.) The Freon was applied to achieve an end concentration of approximately 45-50% by volume and the water was applied at 30.6 ml/cm^2 (7.5 gallons per square foot) of floor area per minute. The test sequence for these two extinguishing agents initiated at 258 mm Hg (considered the least hazardous) and progressed to 600 mm Hg (considered the most

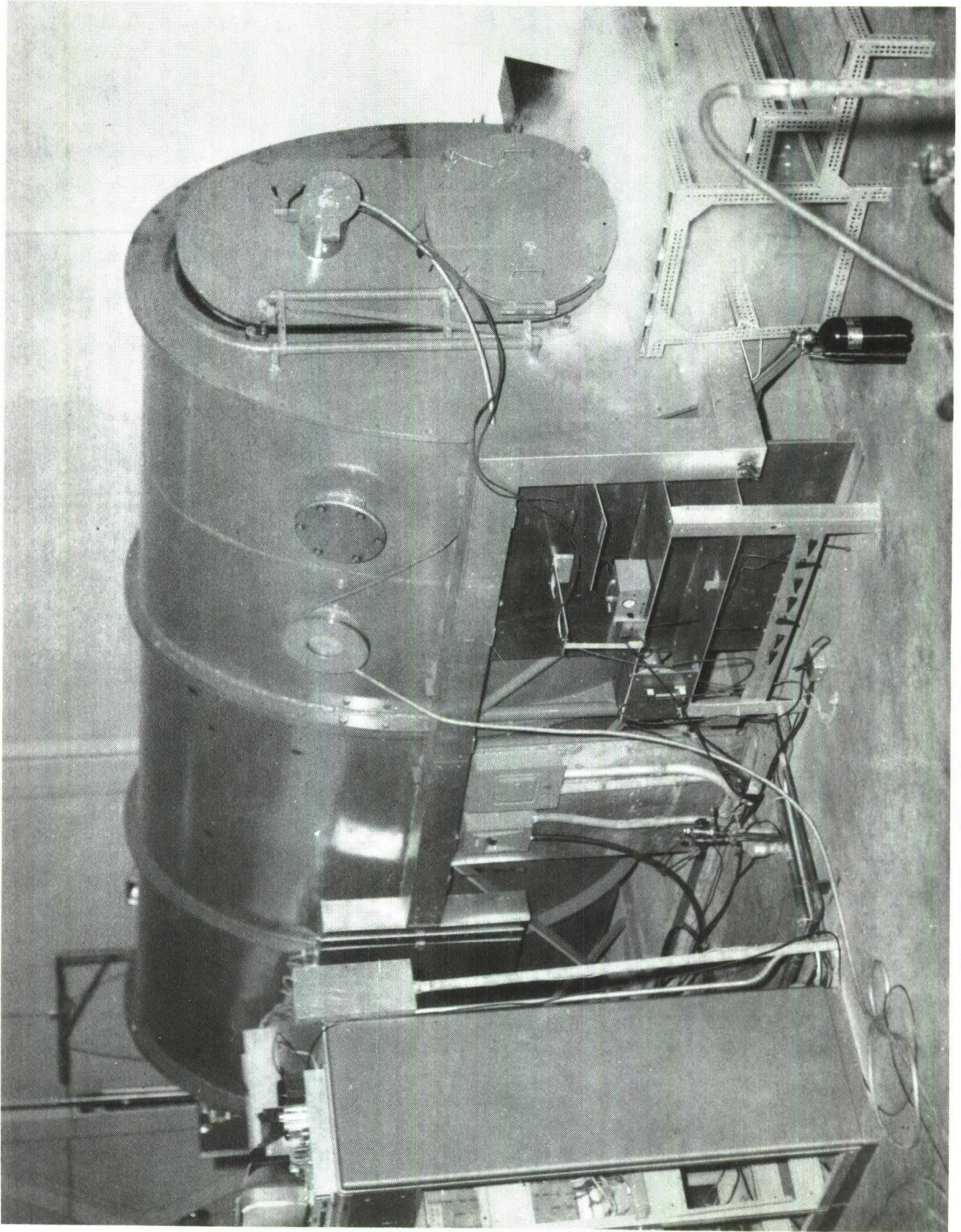


Fig. 1 Two Man Space Environment Simulator

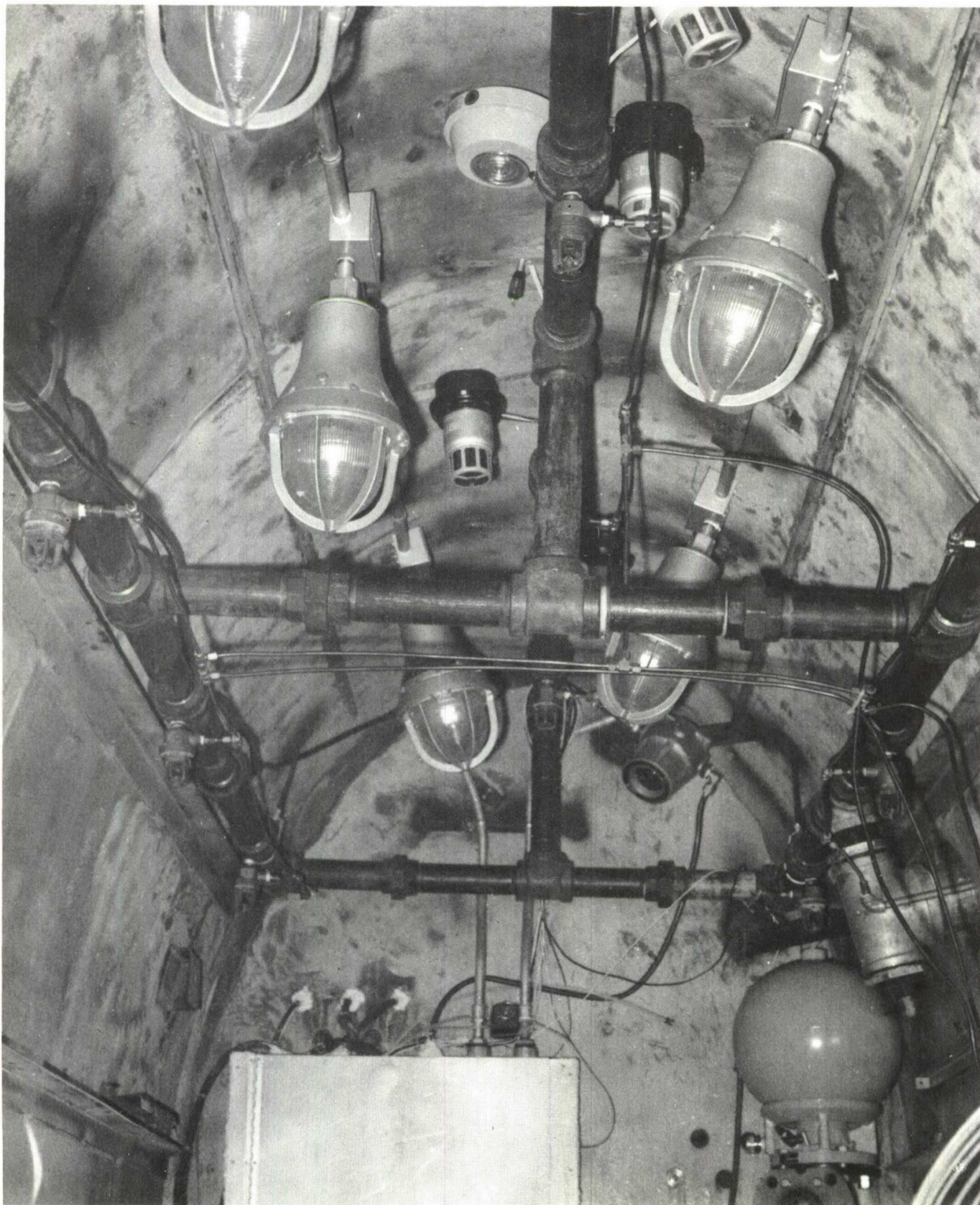


Fig. 2 Inside Test Chamber - East End



Fig. 3 Inside Test Chamber - West End at Door to Interlock Section
74

hazardous) which was the highest pressure which could be attained within the chamber without air penetrating the seal across the chamber door. The test fire in all cases was started by an electrical heater (initiated external to the chamber) heating match heads which ignited and spread the fire to a Kleenex placed over the heater and then to approximately 900 gms of untreated cotton twill uniform material. (See Figure 4.) All detectors were electronically tied into a firing circuit which would automatically trigger the extinguishing agent being tested. The signals from each of the detectors as well as from the Freon system and the water system were recorded on a Visicorder for time reference purposes. High speed motion picture films were taken during the fire and extinguishment. Still photographs were taken prior to the fire and subsequent to the fire in each experiment. (See Figures 5 and 6.)

The data from these experiments are summarized in Reference 2. Pertinent abstracts of this report are contained in Tables 1, 2 and 3.

The following can be concluded from this testing. The ultraviolet detectors provided the most rapid detection due to the nature of the test fires. The ultraviolet detectors would be less susceptible than other light sensitive detectors to false alarms from extraneous light sources. Smoke detectors of the ionization or light transmission types should not be discounted as it may be possible for an impending fire to emit smoke prior to an open flame. Consideration should be

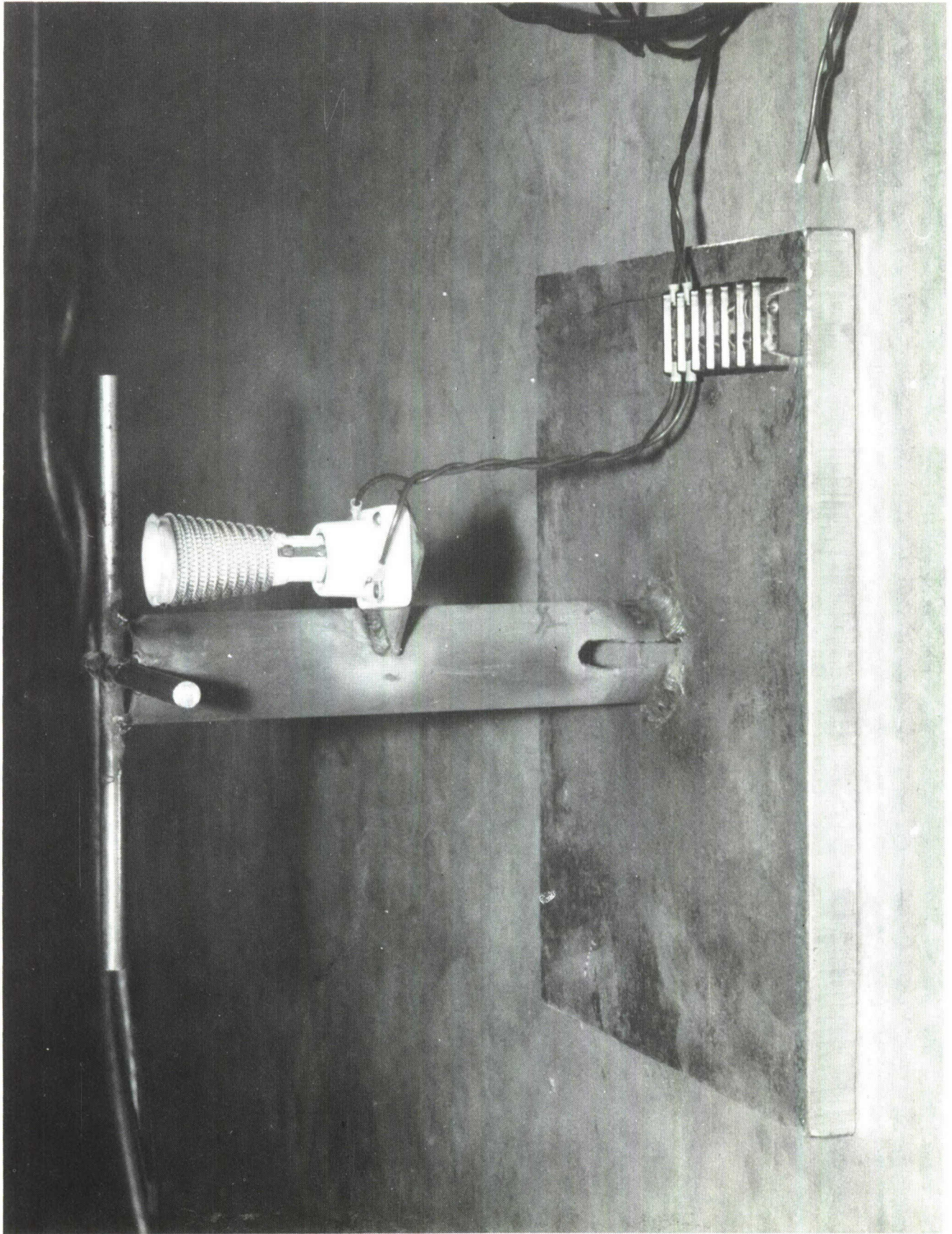


Fig. 4 Frame Used to Support Cloth Used in Test Fires



Fig. 5 Typical Pre-Fire Conditions , Hypobaric Chamber



Fig. 6 Typical Conditions After Water Spray Fire Test

TABLE 1. TIME HISTORY - VISICORDER RECORDS

<u>Test No 1 - Air - 740 mm</u>		<u>Test No 5 - Freon 1301 - 600 mm</u>	
	<u>Seconds</u>		<u>Seconds</u>
No Extinguishing Planned		Fenwal UV Signal	3.285
Pyrotronics No 1	6.625	Shock Signal	3.315
Fenwal UV	6.774	Pyrotronics No 3	3.785
		Pyrotronics No 1	4.590
<u>Test No 2 - Freon 1301 - 260 mm</u>		<u>Test No 6 - Water - 260 mm</u>	
	<u>Seconds</u>		<u>Seconds</u>
Fenwal UV	4.278	Automatic UV Tripped	17.673
Automatic UV	4.312	Water Starts	17.840
Shock Signal	4.293	Water Equilibrium*	18.230
Pyrotronics No 3	4.755	Pyrotronics No 3	19.846
Pyrotronics No 4	4.928	Pyrotronics No 2	20.100
<u>Test No 3 - Freon 1301 - 380 mm</u>		<u>Test No 7 - Water - 380 mm</u>	
	<u>Seconds</u>		<u>Seconds</u>
Fenwal UV	2.996	Automatic UV Tripped	6.483
Automatic UV	3.012	Water Starts	6.600
Shock Signal	3.015	Water Equilibrium	7.100
Pyrotronics No 3	3.670		
Pyrotronics No 4	4.608		
Pyrotronics No 1	4.614		
<u>Test No 4 - Freon 1301 - 650 mm</u>		<u>Test No 8 - Water - 600 mm</u>	
	<u>Seconds</u>		<u>Seconds</u>
System went off prematurely during countdown.		Automatic UV Tripped	3.542
		Water Starts	3.650
		Water Equilibrium	4.070
		Pyrotronics No 3	5.065
Pyrotronics No 1 - Flame Detector with Infrared Cell Pyrotronics No 2 - Smoke Detector - Refractive Beam Pyrotronics No 3 - Smoke Detector - Model F35A - Variable Sensitivity Pyrotronics No 4 - Smoke Detector - Model F5B - Semifixed Sensitivity			

*A pressure transducer was installed on the water supply just outside the chamber. Equilibrium was defined as the point when steady state flow appeared to have been established.

TABLE 2. LOSS OF WEIGHT OF CLOTH IN TEST FIRE

<u>Test No</u>	<u>Conditions</u>	<u>Original Weight (Gram)</u>	<u>Final Weight (Gram)</u>	<u>Loss</u>	<u>Percent</u>
1	Ambient	---	---	---	---
2	Freon - 260 mm	929	885	44	4.8
3	Freon - 380 mm	823	816	7	0.9
4	Freon - Misfire	---	---	---	---
5	Freon - 600 mm	826	830	0	0
6	Water - 260 mm	986	922	64	6.5
7	Water - 380 mm	966	927	39	4.1
8	Water - 600 mm	970	916	54	5.6

TABLE 3. TIME INFORMATION FROM HIGH-SPEED CAMERA

Test No 2	205 ms from initiation of flame to start of discharge 25 ms from start of discharge to loss of vision	200 fr/sec
Test No 3	180 ms from initiation of flame to start of discharge 25 ms from start of discharge to loss of view	
Test No 5	200 ms from initiation of flame to start of discharge 25 ms from start of discharge to loss of view	
Test No 6	200 ms from initiation of flame to start of discharge 50 ms to reach full flow 150 ms apparent extinguishment	
Test No 7	725 ms from initiation of flame to start of discharge 55 ms to reach full flow 820 ms apparent extinguishment	
Test No 8	588 ms from initiation of flame to start of discharge 54 ms to reach full flow 2 sec apparent extinguishment	

given to the location of the smoke detectors in relation to the normal air currents and to the possibility of false alarms from moisture condensation during normal altitude fluctuations within the chamber. Both the Freon and water performed satisfactory fire extinguishment within a reasonable period of time. The advantages and disadvantages of the two systems can be summarized as follows: The water system requires a suitable water source which can meet quantity requirements. This may or may not require additional water supply lines and pumping. The water lines to the chamber would occupy some volume and if the distribution system is internal to the chamber would decrease the available usable volume within the chamber. If the water distribution system is mounted external to the chamber, a hole must be cut into the chamber for each nozzle. This could be quite expensive and could lead to undesirable air leaks into the chamber. Once the water system is discharged all electrical power in the chamber should be discontinued to prevent shorting and electrical shocks to personnel within the chamber. The extinguishing agent is inexpensive. The advantages of the Freon system include its relatively small volume requirements, its ability to extinguish fires behind "shielded" areas and the rapidity with which the fires are extinguished. The Freon system is built around the reliability of the detection system and the rapidity of agent application. A delayed application of the extinguishing agent

would produce toxic pyrolysis products if the fire had a "head start." The toxicity of the unpyrolyzed Freon 1301 in the quantities required is currently being investigated. The noise and blast associated with the release of the extinguishing agent can be solved by engineering design.

Fire Extinguishment in Hyperbaric Environment

Due to the decrease in ignition temperature and increase in burning rate of various materials in the hyperbaric environment, a series of tests were performed to develop a fire extinguishing system for use in this environment. Knowledge gained in the tests in the hypobaric chamber served as a base line for these tests. These tests first involved Freon 1301 and then water.

The chamber used in these tests is a cylindrical vessel approximately 3 meters (9.75 ft) in diameter divided into two test cells, each of which is approximately 3.1 meters (10 ft) in length and has a free volume of approximately 23 cubic meters (800 cu ft). Three 10 liter spheres were mounted approximately 0.6 meters (2 ft) from the floor of one of the test cells with the discharge directed toward the center of the test cell. (See Figure 7.) These spheres were electronically connected to ultraviolet detectors and a firing circuit which automatically discharged the Freon upon sensing a fire. Internal chamber oxygen concentration and temperature fluctuations were normally as follows: The oxygen



Fig. 7 Typical Pre-Fire Conditions , Hyperbaric Chamber

concentration was 20.8% by volume prior to discharge of the Freon 1301 and approximately 18% by volume subsequent to Freon discharge. The quantity of Freon discharged was calculated to be between 5.5% and 6.6% by volume for all tests other than the third test on 3 May. The chamber internal temperature was ambient (approximately 23-24°C) prior to initiating compression. During compression the temperature rose to approximately 48-50°C, however, chamber ventilation immediately upon achieving the test depth decreased the temperature to approximately 30°C. Upon discharge of the Freon, the temperature decreased to approximately 15°C and then rose slowly. The temperature further decreased to approximately 0-5°C during decompression depending upon the rate of decompression. The decompression schedules followed with animals in the chamber were the standard diving charts established by the US Navy. The eight Freon 1301 tests conducted in the hyperbaric chamber will be described in chronological order.

The first test, on 20 April, was performed at six atmospheres air with a manual activation of the Freon release to determine the effects of the Freon on four monkeys, two dogs and six rats. The animals reacted as expected to the noise of compression, i.e., the monkeys and dogs demonstrated anxiety and some of the rats went into audiogenic seizure. Subsequent to Freon release (the end concentration

was calculated to be 6.6% by volume at six atmospheres) the animals appeared normal. The animals were exposed for approximately five minutes prior to the chamber being ventilated. Upon initiation of decompression one of the dogs appeared to go into seizure. This may have been due to the exposure to Freon or to the stresses associated with decompression, i.e., bends, noise, etc. Post exposure examination of the animals revealed no adverse effects. This data tends to conflict with Reference 3 which indicates that short duration (5 minutes) animal (dog) exposures to Freon 1301 in one atmosphere air at concentrations of 5 and 10% by volume followed by the intravenous injection of adrenalin produced irregular heart action. It is assumed that the adrenalin level in the test animals in the hyperbaric chamber was high due to the stresses associated with the Freon discharge. Previous animal exposures (albino rats) to Freon 1301 in one atmosphere air at concentrations of 83.4% by volume revealed that the animals could tolerate the exposure for 15 minutes without adverse effects. (Reference 4) It should be noted that Reference 3 indicates that short duration (3 minutes) human exposures to Freon 1301 in air at concentrations of 7-10% by volume produced a subjective sensation described as a narcotic effect similar to that produced in the first stage of a general anesthesia.

The second test, on 20 April, was performed at 5 atmospheres

air with an automatic release of Freon. The purpose of this test was to determine the efficiency of the fire extinguishing system in air at this pressure. One ultraviolet detector was used to sense the fire which was initiated in the same manner as those in the hypobaric chamber on an untreated cotton uniform. The time delay between visible fire and Freon discharge was longer than had been experienced in the hypobaric chamber, however, this could have been due either to the flame being shielded from the detector or to an increase in UV absorption in the hyperbaric environment. The fire was satisfactorily extinguished (see Figure 8). This test was duplicated on 2 May in 5 atmospheres air and again on 2 May in 6 atmospheres air. The results were similar in each case. These tests pointed out several deficiencies of the system as it was installed. The detection system needed improvement, the dynamic forces created on discharge of the Freon were excessive when directed toward the occupied area, a possibility of injury due to debris from the burst diaphragm (the mechanism of Freon release involved overpressurizing a copper diaphragm) and the loss of vision due to the "fogging" associated with the Freon release into the chamber. In an attempt to estimate the magnitude of the dynamic charges associated with Freon discharge, an additional test was performed on 2 May. The test item was a 57 kg (125 pounds) anthropomorphic dummy seated in a chair centered in



Fig. 8 Typical Post-Fire Conditions after Freon Extinguishment

the chamber. The environment within the chamber was two atmospheres air with an end concentration of approximately 15% by volume Freon. The dummy was dislocated as shown in Figures 9 and 10. See Table 4. Subsequent to these tests it was decided to install a "second generation" Freon system in this chamber in an attempt to design out these adverse effects.

Three additional tests with Freon 1301 in the hyperbaric chamber were performed on 17 and 18 May. The purpose of these tests was to (1) determine the effects of directing the Freon discharge away from the normally occupied area, (2) determine the effects on animals of long duration exposures to the Freon 1301 and (3) determine whether or not a second fire could be ignited with the Freon in the chamber. These tests are described in Reference 2. In the first of these tests the discharge nozzles on the three Freon spheres were pointed so as to discharge parallel to the walls of the chamber and consequently not out into the normally occupied area. This altered direction of discharge did not appear to have an adverse effect on the efficiency of fire extinguishment. Approximately 30 minutes subsequent to the fire and Freon discharge a second ignition was attempted on a different cotton uniform which was suspended approximately 5 feet from the floor. Although the ignition source in the second attempt was identical to that in the first attempt, there was no flame. Some

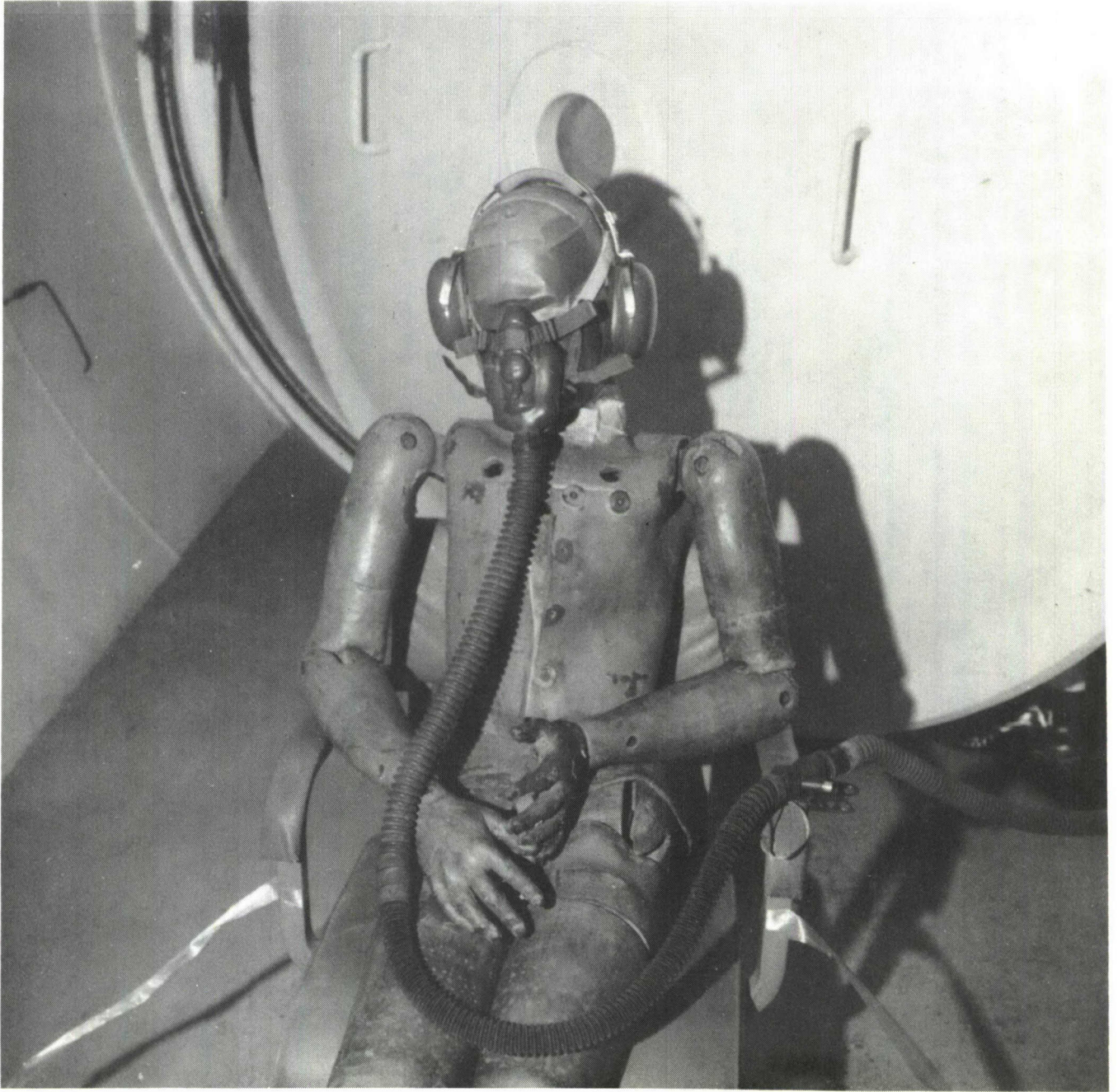


Fig. 9 Position of Dummy Prior to Freon Discharge

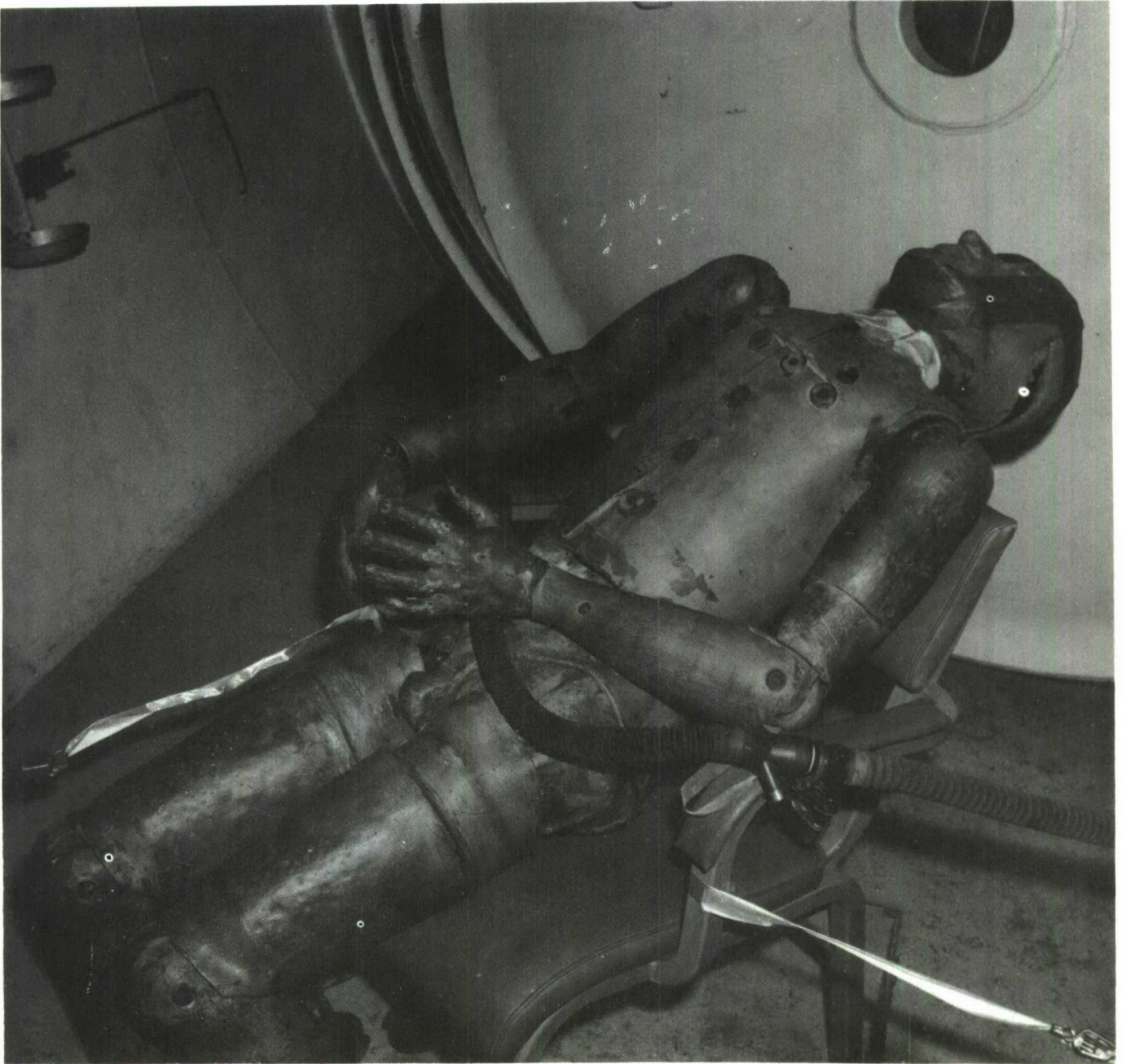


Fig. 10 Position of Dummy after Freon Discharge

TABLE 4

TESTS IN HYPERBARIC CHAMBER

Date	Type Extinguisher	Environment	Test Article
20 April 1967	Freon 1301	6 Atm Air	4 monkeys, 2 dogs, 6 rats
20 April 1967	Freon 1301	5 Atm Air	1 cotton uniform
2 May 1967	Freon 1301	5 Atm Air	1 cotton uniform
2 May 1967	Freon 1301	6 Atm Air	1 cotton uniform
2 May 1967	Freon 1301	2 Atm Air	Dummy
17 May 1967	Freon 1301	6 Atm Air	2 cotton uniforms, second ignition
17 May 1967	Freon 1301	6 Atm Air	1 cotton uniform, animals
18 May 1967	Freon 1301	6 Atm Air	2 cotton uniforms, second ignition, animals
24 May 1967	Water		Various nozzle tests at various atmospheric pressures

smoke did evolve, however. In the second test, on 17 May, two monkeys and ten rats were placed in six atmospheres air and the Freon discharge nozzles were pointed into the walls. A cotton uniform was ignited. The chamber was not ventilated subsequent to Freon discharge and the ascent time was approximately 30 minutes. The fire was satisfactorily extinguished, however, there was a small amount of Freon pyrolysis products. The animals suffered some minor delayed pulmonary edema. There was no apparent narcosis or decompression sickness associated with the exposure or the ascent. The third of these tests, on 18 May, was performed in the same manner as the second, however, the ascent time was approximately twelve hours. In addition a second ignition was attempted some six hours after the first ignition. The first fire was satisfactorily extinguished, the second fire did not ignite; there were some pyrolysis products and some of the animals suffered minor delayed pulmonary edema. Again there was no apparent narcosis or decompression sickness. In summary, the discharge directed into the walls of the chamber (180° from the normally occupied area) had no affect on the efficiency of fire extinguishment, however, visibility subsequent to Freon discharge was enhanced. A second fire would not start with the Freon in the chamber. Some of the test animals demonstrated respiratory irritation from the pyrolysis products,

however, the degree of irritation was not severe and all the animals survived.

To ascertain the effects of increased atmospheric pressures on the discharge patterns of a water spray nozzle, a series of tests were performed on 24 May 1967. These tests which are reported in Reference 5 demonstrated that the degree of dispersion of the water from a spray cone diminishes considerably as the chamber atmospheric pressure increases even though the water static and dynamic pressure differentials (water line to chamber) remain the same. This data was used in the preliminary design of a water extinguishing system for this chamber which at this date (15 August 1967) has not been installed.

In summary, a Freon system can be designed which will efficiently extinguish fires in a hyperbaric environment. There are some questions which remain unanswered, however, regarding the human toxicity of Freon 1301 in the concentrations required. The pyrolysis products could pose a problem if the chamber is unventilated or if the chamber is not equipped with supplied air respirators. Potential problems of dynamic forces, debris from the burst diaphragm and noise can be eliminated in the design. If a water system is used consideration must be given to provide a pressurized water source or perhaps a booster pump to provide the designed pressure differential. Additionally, one must consider the decrease in the water spray pattern at higher

chamber pressures .

Protective Clothing Investigations

The purpose of the protective clothing investigations was to determine the qualitative degree of protection from fires provided by various *Beta cloth uniforms. Preliminary literature reviews and small scale testing indicated that fiberglass cloth would be the most noncombustible fabric. These uniform tests were performed in the same hypobaric chamber which was used in the fire extinguishment evaluations. In all tests a newly sacrificed unshaven pig of approximately 52-57 Kg (115-125 pounds) was placed in the uniform to be tested and suspended by its forelegs from the top of the chamber. A fire was then initiated on a cotton uniform adjacent to the clothed pig in the manner previously described. All uniform tests were performed in greater than 98% oxygen at 380 mm Hg. The installed water extinguishing system was manually activated on command at the discretion of the test director. The uniform tests were performed at approximately 25°C.

The first uniform tested was a woven 35 x 24 threads per centimeter (90 x 60 threads per inch), single piece beta cloth uniform

*Owens-Corning Fiberglas Corporation trademark. Beta yarn is composed of glass B-filaments (0.00014 inches in diameter).

fabricated to resemble a normal work coverall. The cotton material which was burned was hung vertically approximately 30 cm (12 inches) from the test uniform. Open flame was visible for approximately 7 seconds prior to initiating the water extinguishing system for a 10 second flow. The emergency dump valves on the chamber were opened so as to repressurize the chamber immediately after the water started flowing. In this test the fire did not propagate to the test uniform or to the animal, consequently, the test uniform was not damaged and the animal suffered no thermal injury. The fire which had been initiated on the cotton material was extinguished at the end of the 10 second flow. The immediate dump did not appear to have any effect on the efficiency of extinguishment.

The second uniform test used the same beta cloth uniform, however, the cotton material on which the fire was ignited was positioned so that it touched the test uniform at the lower buttocks and at the back of the head. Approximately 13 cm (5 inches) separated the cotton uniform from the test uniform at the maximum separation distance. See Figure 11. Open flame was visible for approximately 11.5 seconds prior to activation of the water extinguishing system for a 10 second flow. Again the emergency dump valves were opened immediately after the water flow initiated. In this test the flames from the cotton material melted parts of the test uniform and ignited the hair on the



Fig. 11 Pig in Woven Beta Cloth Uniform Prior to Fire

pig under the uniform. The fire on the pig's surface then propagated around the pig and under the test uniform where the test uniform did not fit tight. The water extinguishing system did not stop this propagation under the uniform as the water could not penetrate the tightly woven beta cloth. In fact, the hair on the pig's body under the test uniform continued to burn at the end of the 10 second water flow.

See Figures 12, 13 and 14.

A test of a knitted fiberglass uniform was performed on 6 June. This fabric had much more porosity than the uniform used in the previous tests and was constructed in a tight fitting two piece style similar to long underwear. Two different knits (one much more open than the other) were used in this test. The test fire was positioned and ignited in the same manner as in the second uniform test. Open flame was visible for approximately 7.5 seconds prior to initiation of the water extinguishing system. The fire appeared much more intense than the second uniform test fire and engulfed the entire back of the test animal. The flames melted the test uniform up the back of the test animal and the animal suffered second and third degree burns where the flames melted through. The fire did not propagate around the surface of the test animal under either of the knits other than at the buttocks where the uniform did not fit tight. See Figures 15 thru 18. This may have been due to either the tight fitting uniform or the

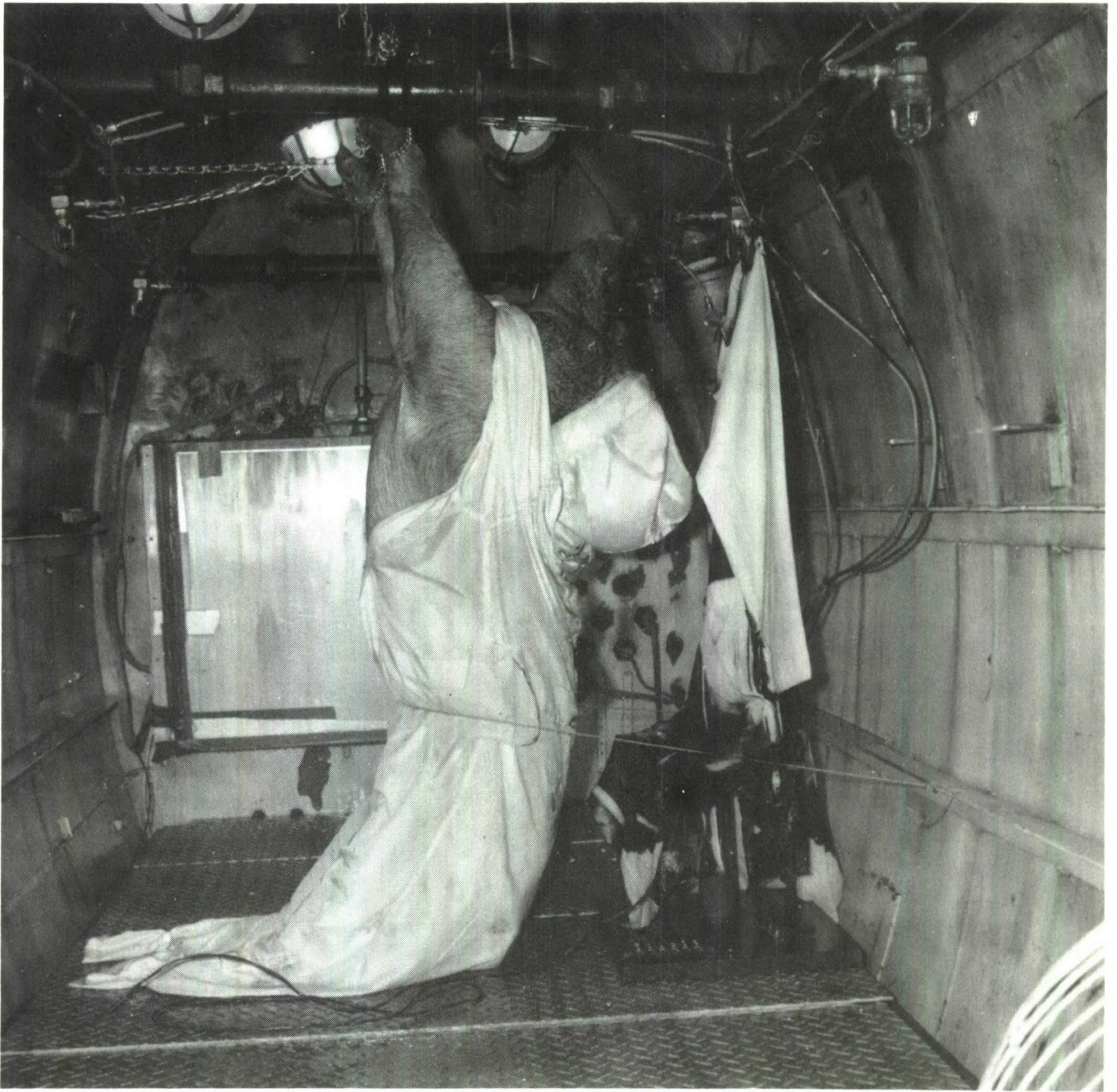


Fig. 12 Pig in Woven Beta Cloth Uniform after Fire



Fig 13. Back View of Piq with Uniform Removed



Fig. 14 Side View of Pig with Uniform Removed

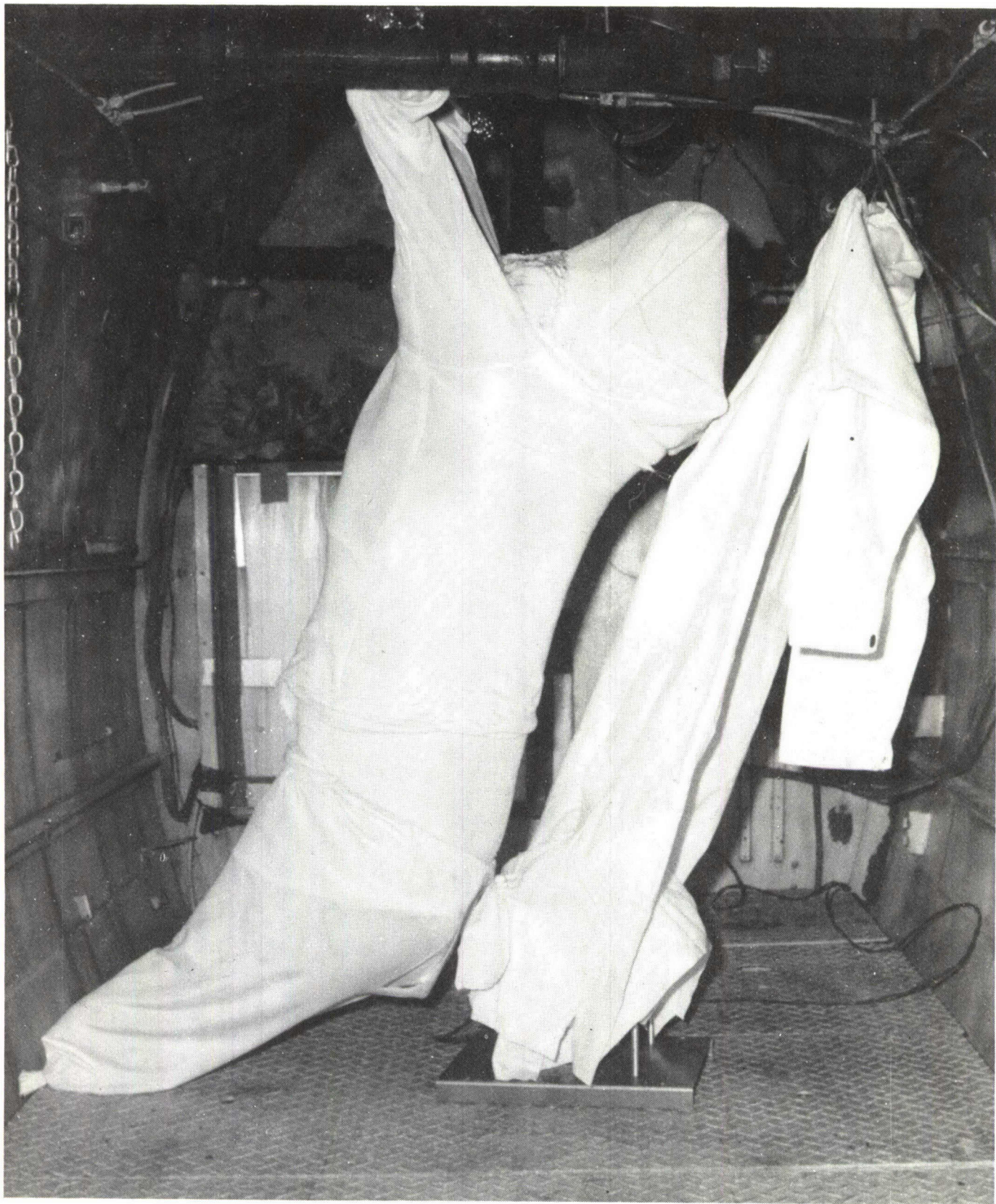


Fig. 15 Pig in Knitted Beta Cloth Uniform Prior to Fire
101

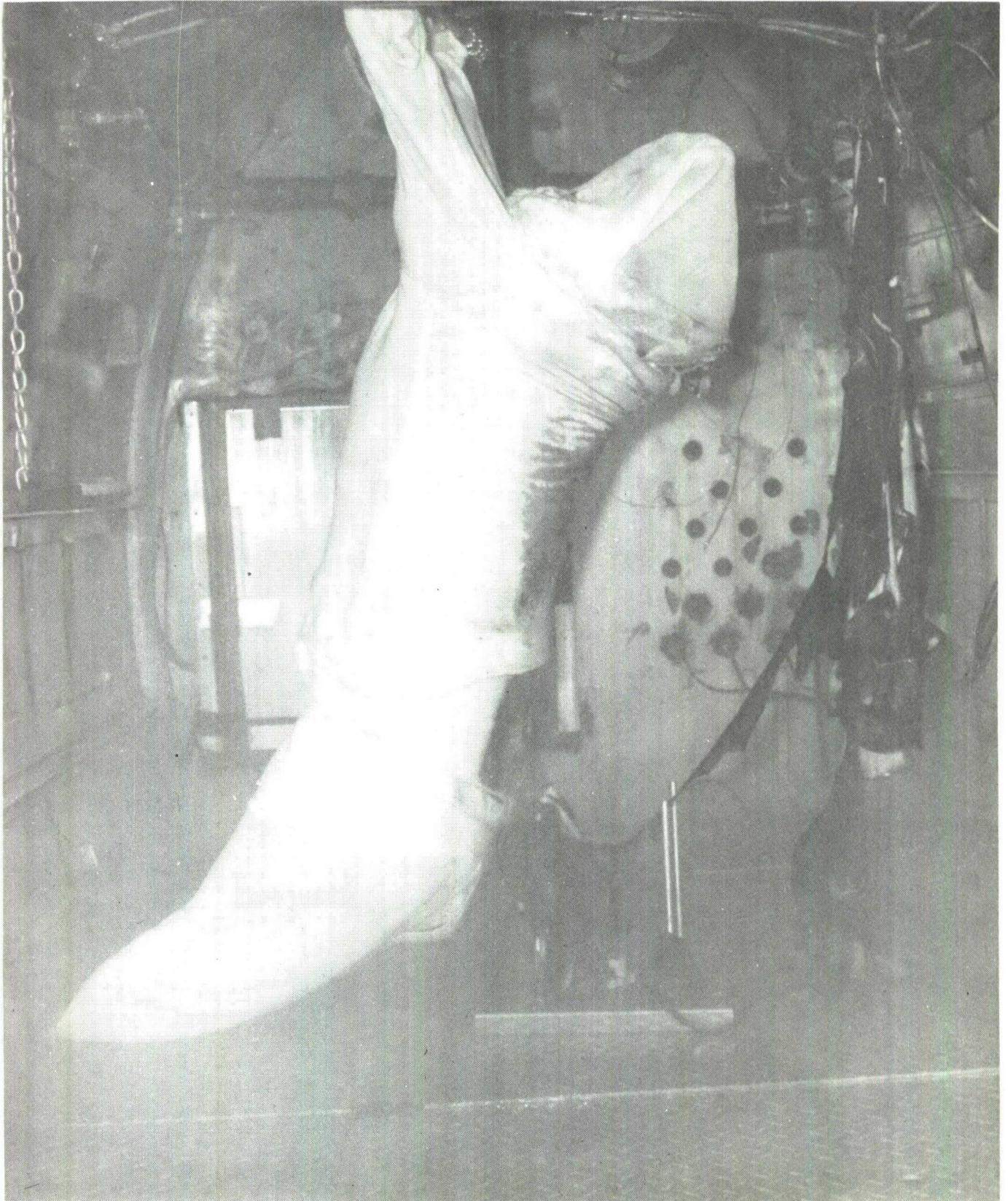


Fig. 16 Pig in Knitted Beta Cloth Uniform after Fire
102

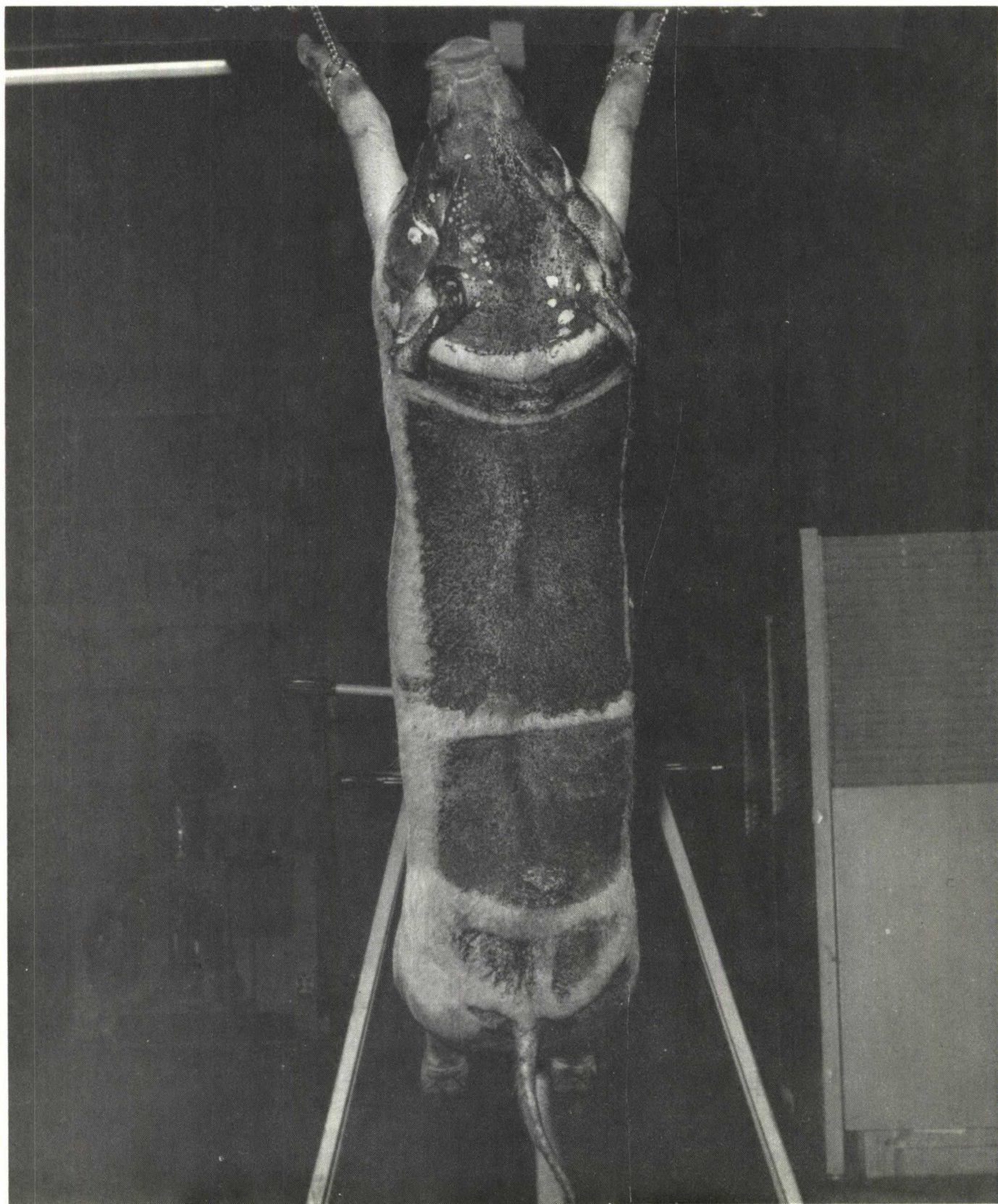


Fig. 17 Back View of Pig with Uniform Removed

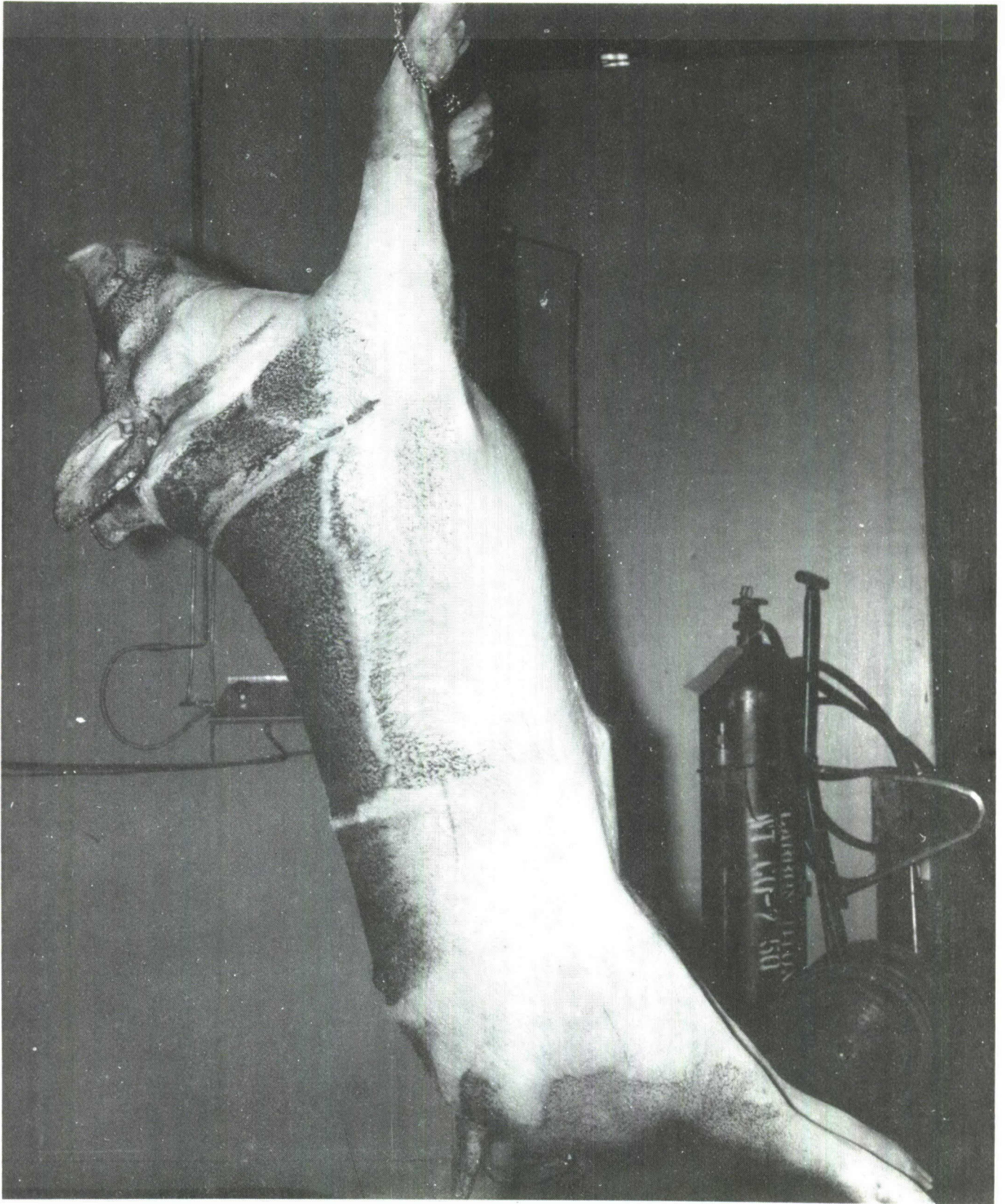


Fig 18 Side View of Pig with Uniform Removed
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ability of the fire extinguishing agent to penetrate the test uniform or a combination of the two.

From these uniform tests it appears that the most effective uniform design would be a knitted tight fitting noncombustible uniform which would offer protection from the fire and which would not be excessively hot during normal usage.

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TOXICITY OF FREON 1301

Dr A. A. Thomas
Director, Toxic Hazards Division
6570 Aerospace Medical Research Laboratories
Wright-Patterson Air Force Base Ohio

The paper title should be the Toxicity of the Pyrolysis Products of Freon 1301. By a happy coincidence this work was done last year by Aerojet-General Corporation who is our inhouse contractor in the Toxic Hazards Research Unit. The work was done by Mr Ed Vernot so I will ask him to present a portion of the paper.

INHALATION TOXICITY AND CHEMISTRY OF PYROLYSIS PRODUCTS OF BROMOTRIFLUOROMETHANE

Mr E. H. Vernot
Aerojet-General Corporation
Toxic Hazards Research Unit
Overlook Branch
PO Box 3067
Dayton Ohio 45431

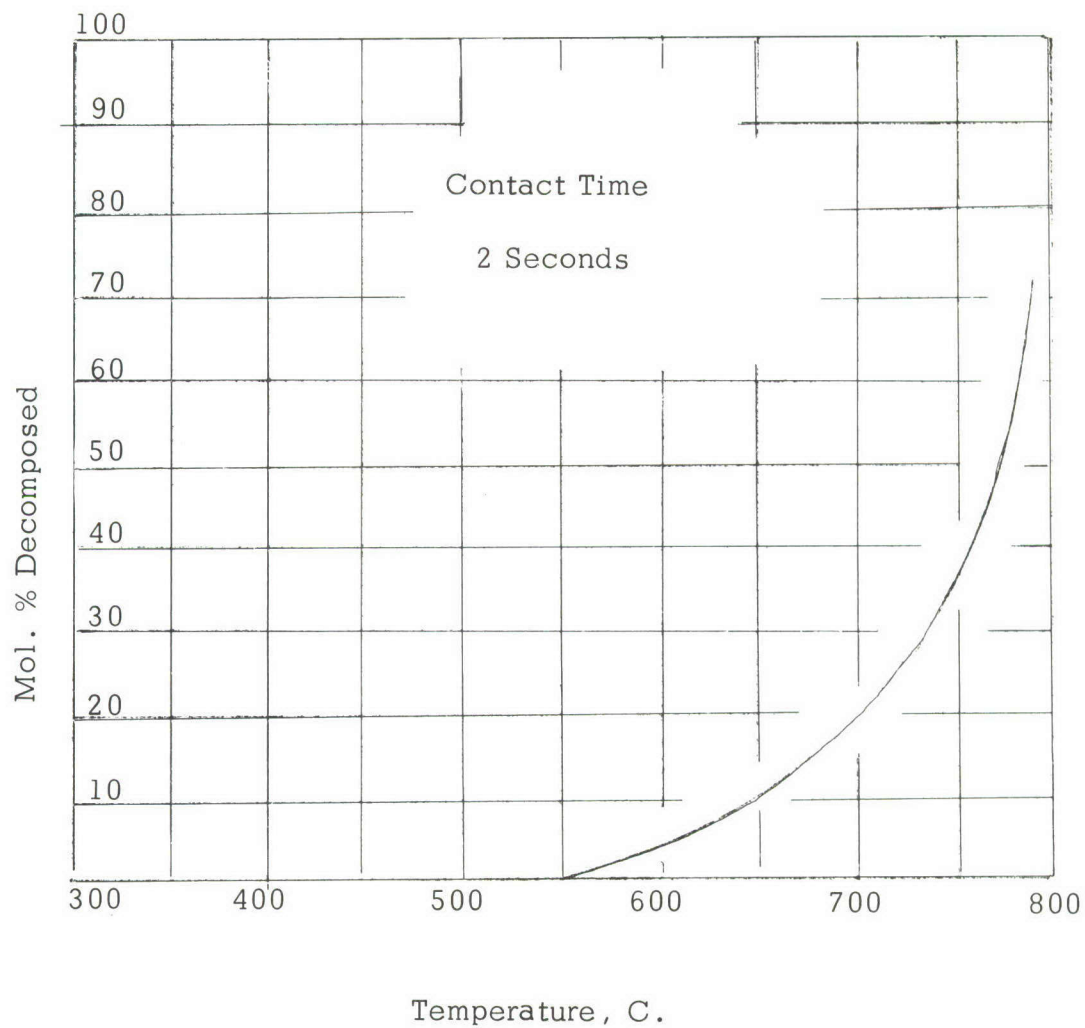
Introduction

Monobromotrifluoromethane (CBrF_3) holds great interest as a fire extinguishing material because of its effectiveness at reasonably low concentrations, its volatility and its low toxicity. Engibus and Torkelson (1960) reported the $\text{LC}_{50/15}$ minutes for the pure material to be 834,000 ppm or 83.4%. At this concentration, the animals die of asphyxiation, so it may be assumed that CBrF_3 is essentially non-toxic in short term exposures. In the high temperature of a flame, however, extensive decomposition and rearrangement of the extinguishing chemical occurs leading to the formation of materials much more toxic than the parent. Since previous work (Engibus and Torkelson) had shown that CBrF_3 should be completely decomposed at 800°C , this temperature was chosen for pyrolysis of the material. Figure 1 illustrates the extent of CBrF_3 decomposition at various temperatures.

Materials and Methods

Longley inhalation exposure chambers were used in this series

FIGURE 1



CBrF_3 DECOMPOSITION VS TEMPERATURE

of experiments and have been described elsewhere, J. D. MacEwen (1965). Groups of 10 rats each were exposed in these chambers to varying concentrations of pyrolyzed CBrF_3 . The CBrF_3 was pyrolyzed in the flame of a modified flame photometer analyzer burner. The inner capillary of the burner was removed, the oxygen and CBrF_3 premixed and the mixture delivered through the channel formed by removal of the capillary. Hydrogen was passed through the burner in the normal manner. The hydrogen-oxygen ratio was adjusted to give the desired flame temperature of 800°C as measured by a chromel-alumel thermocouple.

The exposure time was kept constant at fifteen minutes and the concentration of CBrF_3 varied from 3500 to 8000 ppm. Since percent pyrolysis (calculated from CBrF_3 analyses before and during pyrolysis) averaged 55%, the animals were exposed to the pyrolysis products of 1700 to 4500 ppm CBrF_3 .

Results and Discussion

Figure 2 is a plot of the log of pyrolyzed CBrF_3 concentration versus percent mortality on a probability scale. Classical toxicology predicts a straight line for this plot, and Figure 2 exhibits good linear behavior. The concentration equivalent to 50% mortality or LC_{50} is seen to be 2300 ppm. That is to say that 2300 ppm of CBrF_3 , 100% pyrolyzed as outlined in this experiment, would, if

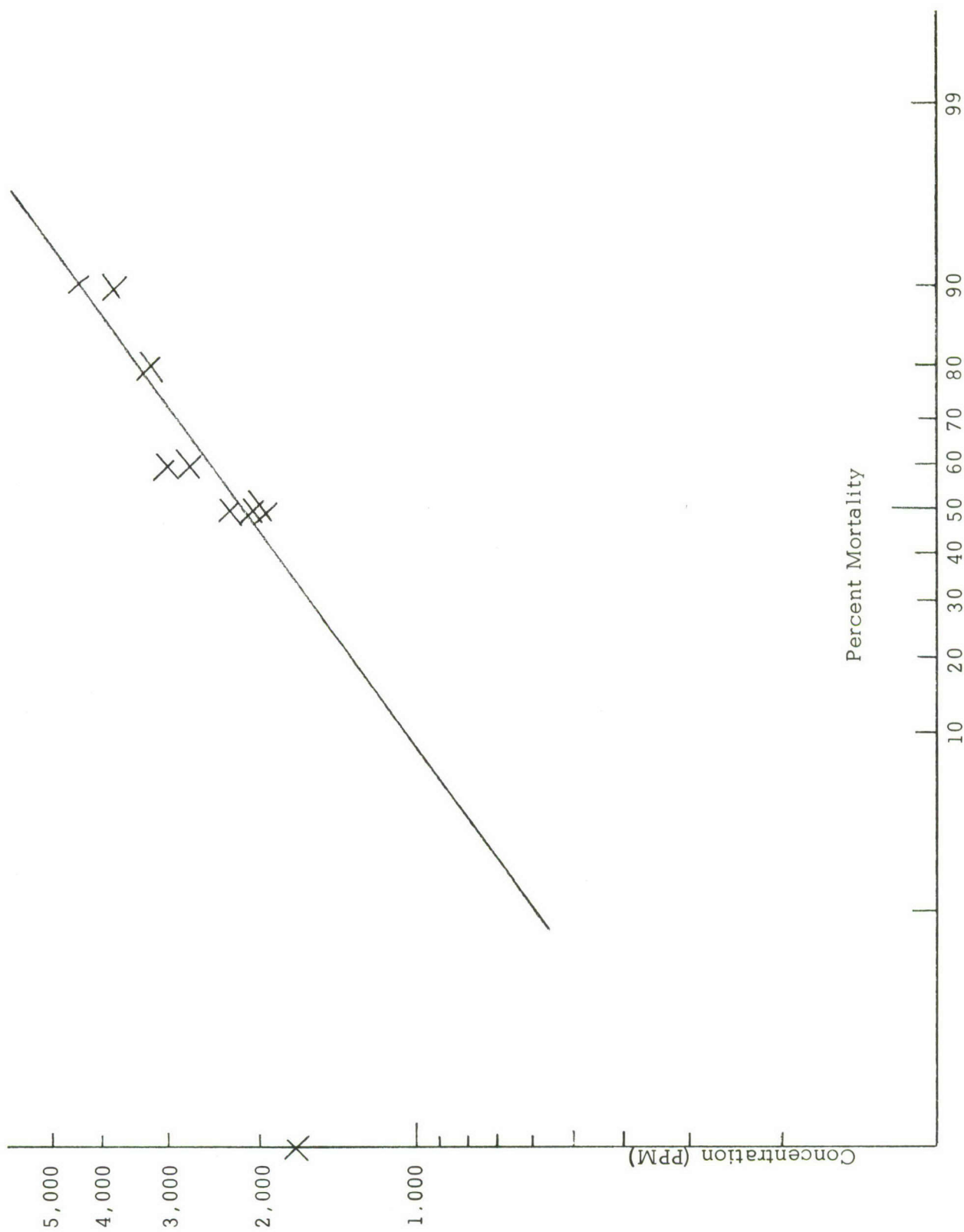


Figure 2 Concentration of Pyrolyzed CBrF₃ vs Percent Mortality

run a statistically sufficient number of times , cause half of rats exposed for fifteen minutes to die. The material was not completely pyrolyzed in these experiments , probably because the residence time in the atomizer burner was less than a second. Table 1 shows that animals surviving exposure did suffer some loss in weight in succeeding days . After fourteen days , when all the animals were sacrificed , they had begun to recover , and their appearance was normal.

Two earlier investigations into the approximately lethal concentration (ALC) of pyrolyzed CBrF_3 at fifteen minutes had been made. Workers at the Army Chemical Center, C. C. Comstock, et al (1950), pyrolyzed CBrF_3 vapors by passing them through an iron pipe at 800°C for one second. University of Cincinnati investigators used an inconel pipe at 1090°C , F. J. Treon, et al (1957). Table 2 compares the results obtained in these studies with ours. Both Comstock, et al and Treon, et al used approximate lethal concentrations or $\text{ALC}_{15 \text{ minute}}$ values as measures of toxicity, and, as can be seen, agreement between the values reported from their laboratories is fairly good. The ALC value is a measure of the concentration of contaminant sufficient to kill all experimental animals (in this case rats) during or after fifteen minutes exposure. If our experimental mortality values in Figure 2 are extrapolated to 99% to give an estimate of

TABLE 1

Mean Weights of Rats Surviving Exposure to the
Pyrolysis Products of CBrF_3

Exposure ppm as CBrF_3	Day Post Exposure				Number of Rats
	0	3	7	14	
1700	235	208	220	230	10
1850*	196	144	hd	201	5
1950	224	185	197	211	5
2100	182	151	150	178	5
2270*	193	179	191	217	6
2300	205	nd	184	207	5
2750	189	172	178	207	4
3075	201	160	164	164	4
3250	208	156	163	216	4
3780	220	198	183	216	1
4475	201	258	164	203	1

*Material meeting military specification MIL-B-4394-B.
Other data are from material meeting MIL-B-12218-A.

TABLE 2

Comparison of Pyrolyzed CBrF₃ Toxicities
Measured in Three Laboratories

<u>Laboratory</u>	<u>Pyrolysis Method</u>	<u>Temperature</u>	<u>Toxicity (15 minutes)</u>
Comstock, et al	Iron Pipe	800°C	ALC - 14,000 ppm
Treon, et al	Inconel Pipe	1090°C	ALC - 17,000 ppm
THRU	H ₂ -O ₂ Flame	800°C	LC ₅₀ - 2,300 ppm

the ALC for CBrF_3 , we find it to be 8000 ppm. This concentration represents pyrolyzed CBrF_3 , not total CBrF_3 concentration (pyrolyzed and unpyrolyzed) in the exposure chamber. To compare our values with the earlier results, we must convert them to total CBrF_3 concentrations. Since our pyrolysis averaged 55%, our experiments indicate an $\text{ALC}_{50/15}$ minutes of 14,500 ppm, a value that compares well with earlier ones.

It might appear at first, to be surprising that all three investigations showed approximately the same toxicity for pyrolyzed CBrF_3 , since the methods of pyrolysis were so different. However, the attainment of an 800°C flame temperature restricted our hydrogen to oxygen ratio to about 3 to 1 which meant there was a 50% excess of hydrogen in the flame over that necessary to combine with oxygen. We obtained, therefore, essentially reducing conditions in the flame, corresponding to the previous investigations which were also run under non-oxidizing conditions.

This excess hydrogen available for combination with CBrF_3 breakdown products is reflected in the analysis of the pyrolysis products as shown in Table 3. HF represents the highest concentration of materials obtained from degradation. At the LC_{50} value of pyrolyzed CBrF_3 (2300 ppm), 2480 ppm of HF was formed. This agrees well with the $\text{LC}_{50/15}$ minute value of 2700 ppm HF reported

TABLE 3

CBrF₃ Pyrolysis Products

	<u>Pre-Pyrolysis</u>	<u>Pyrolyzed</u>	<u>HF</u>	<u>HBr</u>	<u>Br₂</u>
Concentration, ppm	3860	2200	2320	160	250
% of Available		57	35	7.5	23

by Carson, et al (1961) for rats. It appears, therefore, that the toxicity of CBrF_3 , pyrolyzed as in our experiments, can be explained satisfactorily on the basis of the HF formed.

Only a minor amount of the pyrolyzed CBrF_3 could be accounted for by chemical analysis - 35% of the available fluorine as HF and 30.5% of the available bromine, 7.5% as HBr and 23% as Br_2 . No satisfactory explanation for poor bromine recovery has been accomplished, but some interesting results were obtained with respect to fluorine upon mass spectrometric examination of the chamber atmosphere during exposure. Much the strongest peak obtained was at mass number 85, equivalent to an $-\text{OCF}_3$ fragment. The highest mass number peak obtained was at m/e 282. A molecule of that molecular weight and containing $-\text{OCF}_3$ groups is $\text{CF}_3\text{OCH}_2\text{CH}(\text{OCF}_3)_2$. Without assigning a great deal of confidence to the latter formulation, it is possible that oxygen is replacing the bromine in CBrF_3 with subsequent condensation of the fragments to give fluorinated, oxygenated hydrocarbons. One would expect these to have a low toxicity compared to HF.

One expression of caution is in order in applying both toxicological and chemical results obtained here to 100% oxygen fires. As has been noted, all work done thus far has pyrolyzed CBrF_3 under essentially non-oxidizing conditions. The products obtained by pyrolysis in an

oxygen rich flame, and their toxicity, may be very different from those obtained in the past.

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PATHOLOGY REPORT ON THE TOXICITY OF THE
PYROLYSIS PRODUCTS OF FREON 1301

Dr A. A. Thomas
Director, Toxic Hazards Division
6570 Aerospace Medical Research Laboratories
Wright-Patterson Air Force Base Ohio

First of all there was a typical delayed death pattern in these animals, which is somewhat of a different story than what you see with chlorobromomethane pyrolysis products where there is no late death. Those animals which received a sufficiently high dose died immediately during exposure or between the third and the fifth day after exposure (we kept the survivors for fourteen days). In the immediate deaths, the gross pathology simply consisted of severe pulmonary changes - diffuse congestion, edema and hemorrhage - with some emphysema in a portion of the animals. In those animals which survived for a couple of days and then died, the pulmonary changes were significant but not as severe as in the acute group. There was some focal hemorrhage, congestion and mild interstitial edema. There was a frequent finding of cellular infiltration of the alveolar spaces with interstitial pneumonitis and proliferative and fibrotic peribronchitis. This points out the occupational medicine aspect of these exposures as persons so exposed could very likely be disabled for the rest of their lives on account of the proliferative nature of the lesion.

The animals which were exposed to the LC50 concentration also showed severe eye and nose irritation and, in fact, the cornea was etched in many instances resulting in dense white corneal opacity. This is probably a straight fluorine effect on the cornea. Those animals which survived the whole fourteen days (and received a very low dose of pyrolysis products) showed some slight pulmonary congestion and emphysema, but they appeared to be healthy.

This is about the pathology story. Apparently it is a matter of how long it takes to put the fire out, because the time to extinction is directly proportional to the amount of pyrolysis products formed. Therefore, it is very obvious that we need automatic triggering to extinguish the fire as soon as possible and thus keep the formation of pyrolysis products to an absolute minimum.

GENERAL REMARKS

Colonel A. G. Swan
Director of Research & Development
Aerospace Medical Division
Brooks Air Force Base Texas

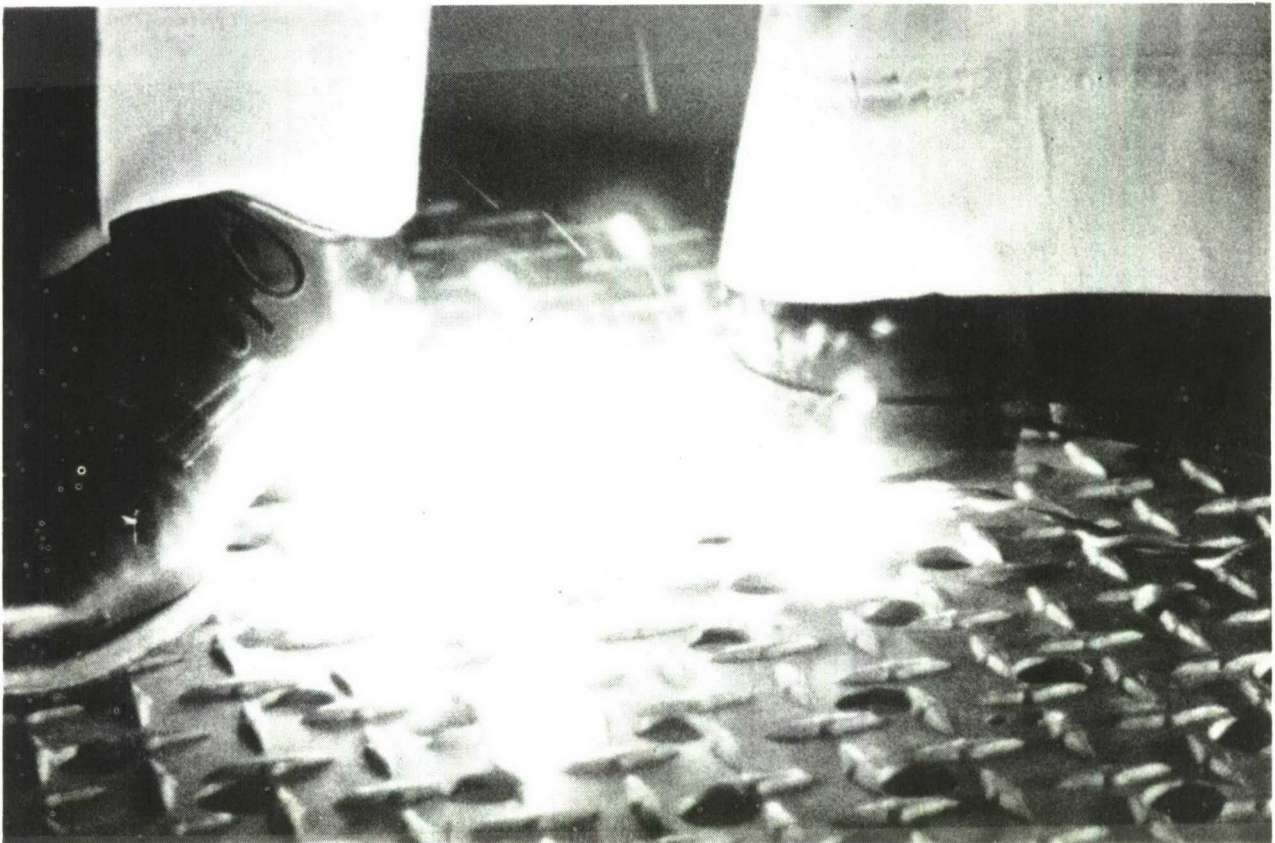
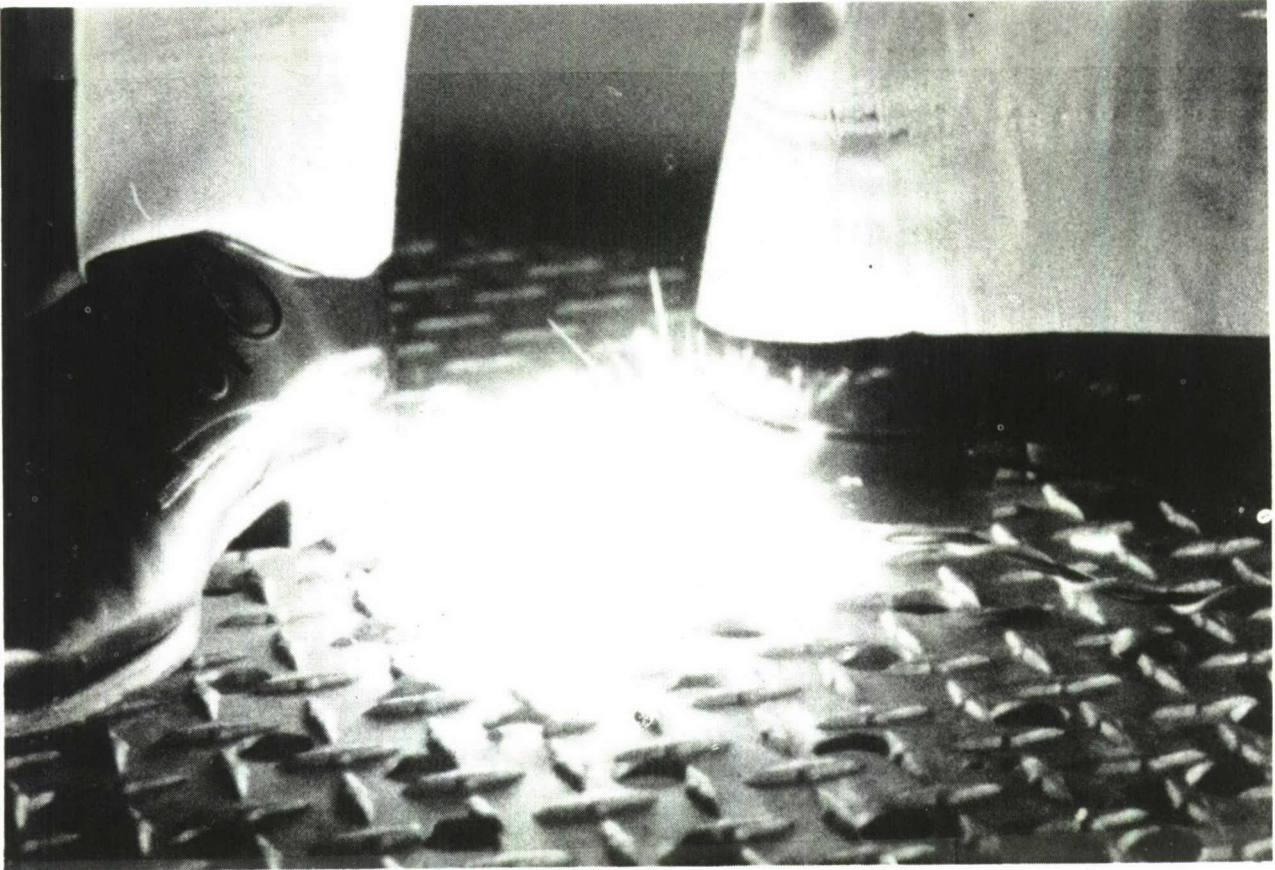
I would like to emphasize that the evaluations of fire extinguishing systems that have been conducted to date have been done with off-the-shelf equipment to determine whether or not such systems would work in environments containing high concentrations of oxygen. It certainly has not given the engineer an opportunity to design an optimal system or to fabricate the optimal equipment to use for extinguishing fires. We intend to improve these systems by designing, fabricating and installing what we believe will be an optimal configuration.

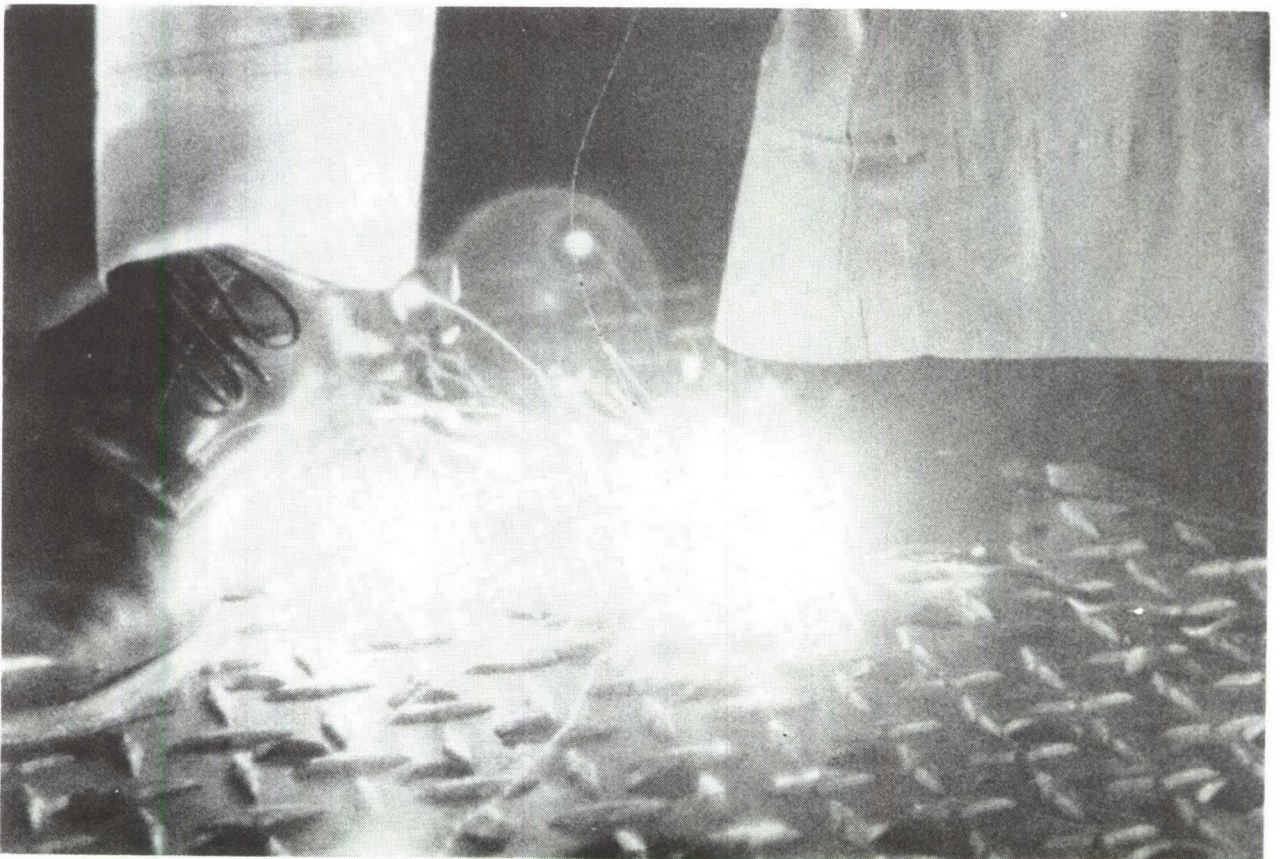
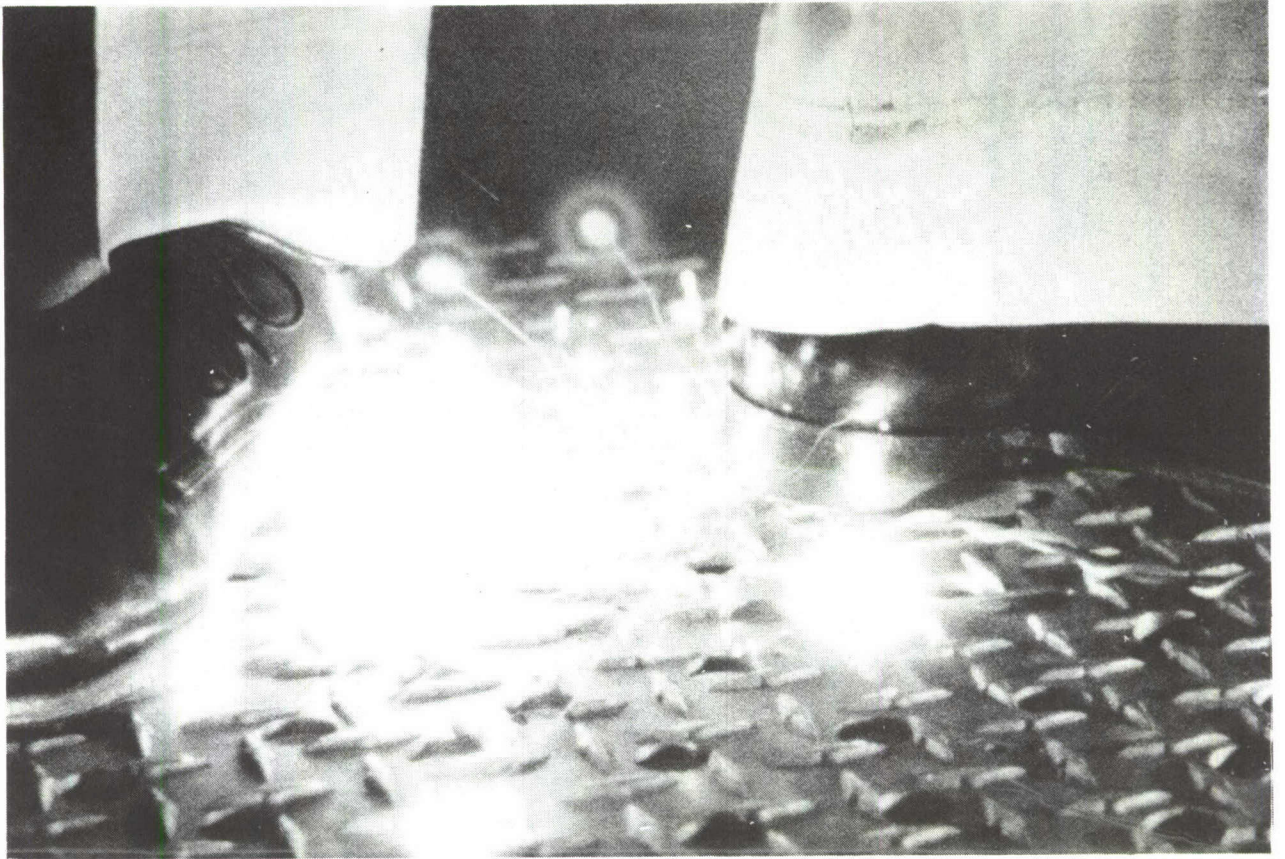
Let me say a few words about inhibitors. Some time ago Dr R. G. Shuttleworth of the South African Embassy in Washington communicated with us suggesting that small quantities of certain halogens could be used as inhibitors. Freon 1301 is one of the inhibitors he suggested and we intend to evaluate it further. As Captain Carter pointed out to you this morning, he attempted to ignite a second fire, after the Freon had put out an initial fire in the hyperbaric chamber, some six hours after the first fire. The Freon was still in the chamber. There was some smoking and a small amount of smoldering in the material but no active fire. We intend to, in the near future, evaluate inhibitors at

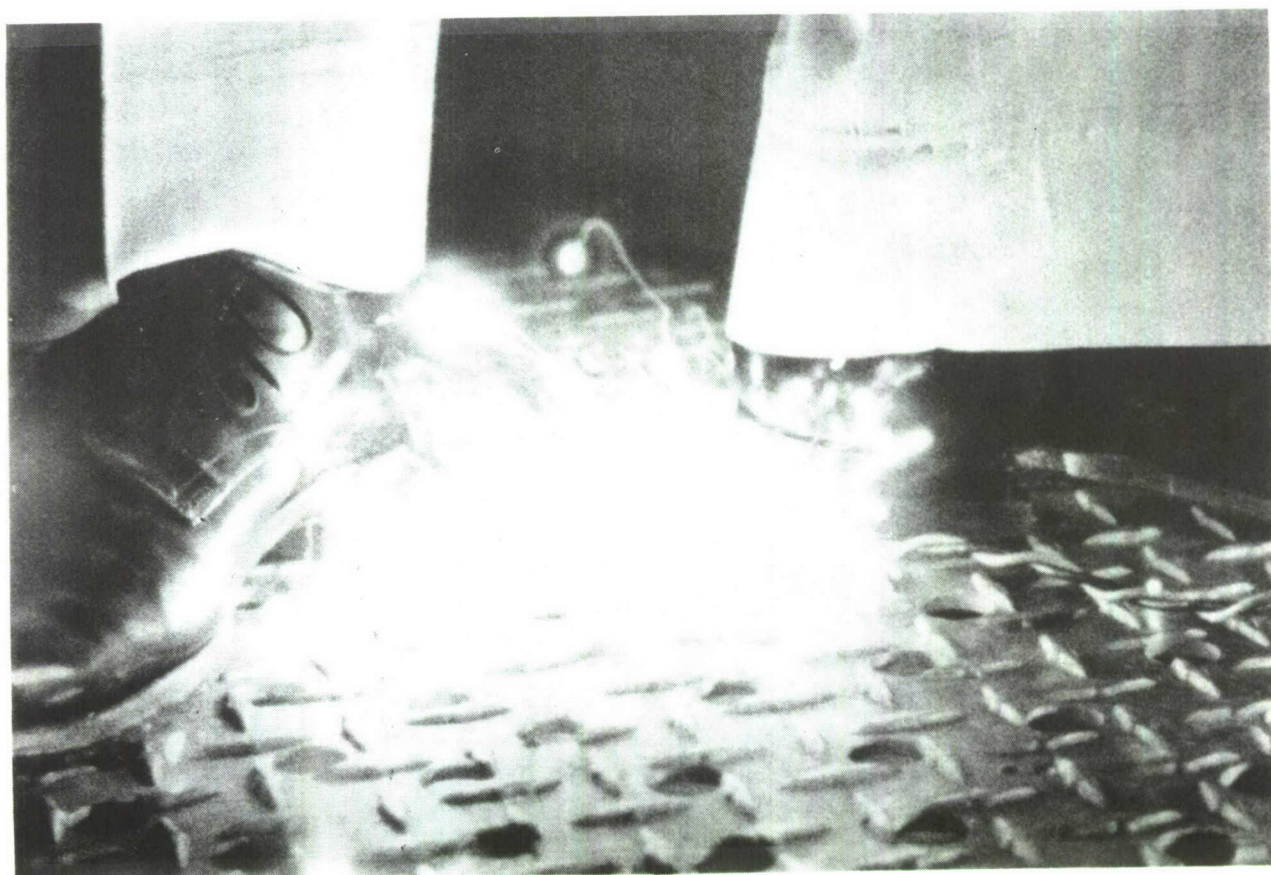
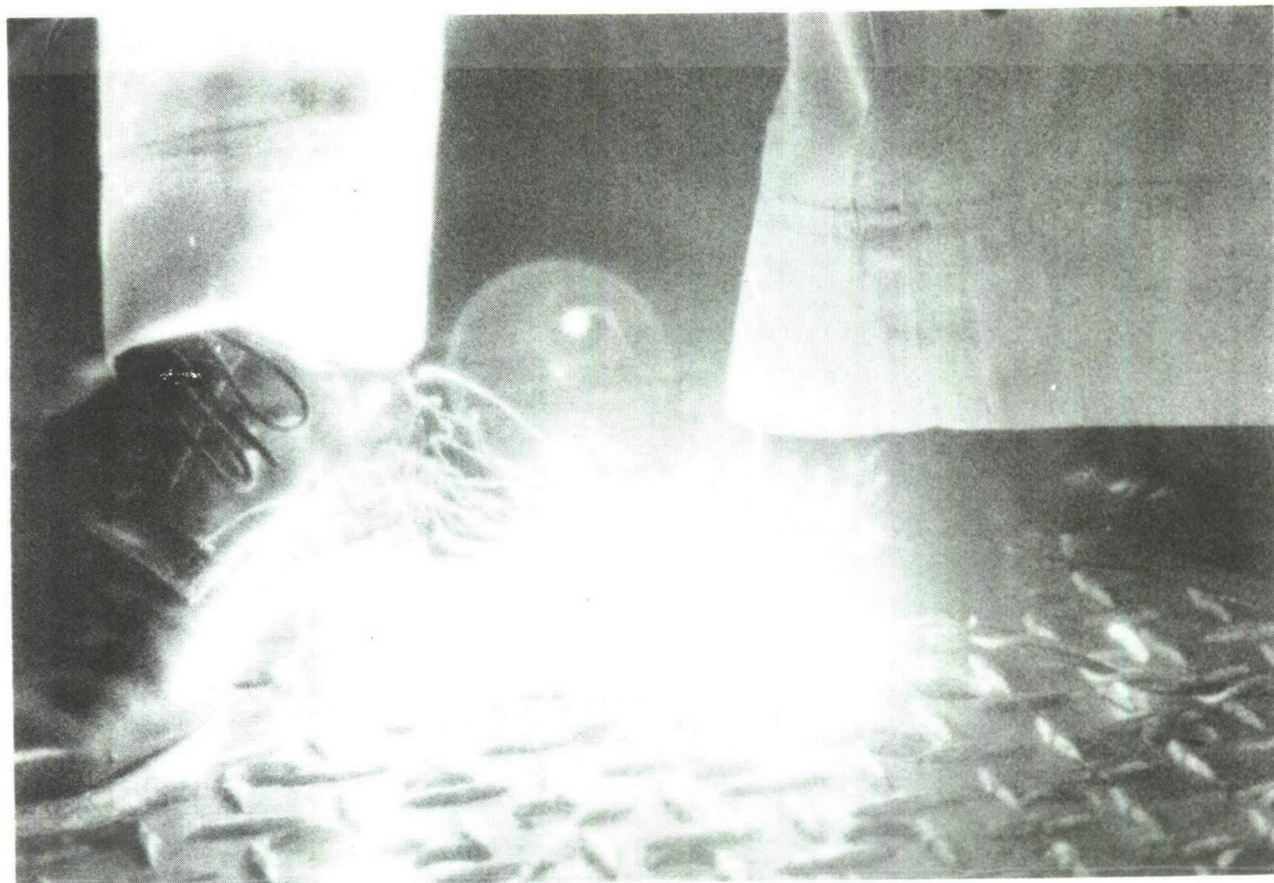
the lower pressures , at half an atmosphere or less and 100% oxygen to determine whether an inhibitor is a practical fire prevention agent. I am sure Dr Shuttleworth has also published some technical articles on this subject.

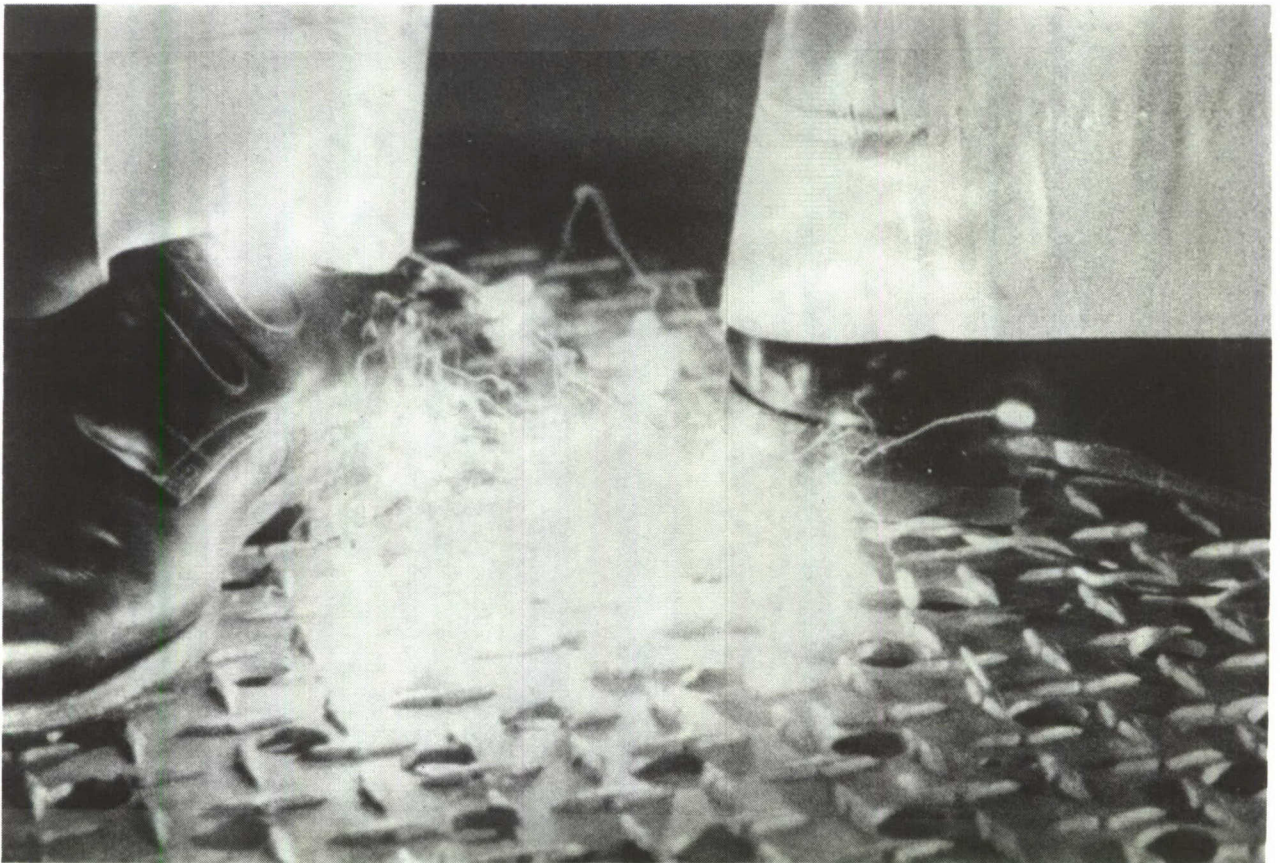
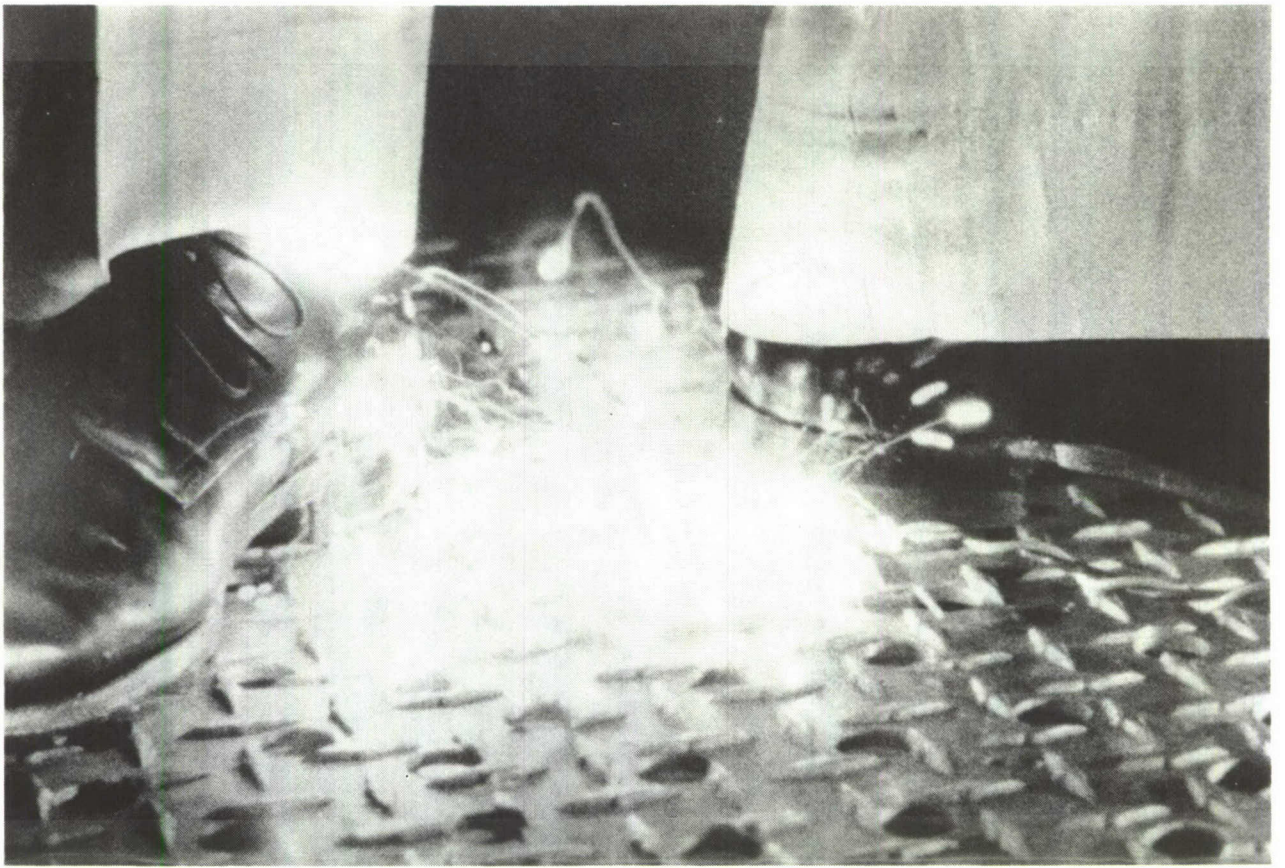
There is another thing that I would like to acknowledge regarding the number of items that we have gone back into the laboratory to confirm , and the off-the-shelf equipment we have used in trying to draw conclusions . We have just about confirmed all the reports on the subject which the RAF published approximately a year ago . We agree with the characteristics of burning , the nap fire and the fact that one must initiate extinguishment within five to twenty seconds . We agree with them on the directivity requirements of water spray . The last time I talked to Dr Denison in Farnborough the RAF was considering increasing the water spray density . I believe that in the last report five milliliters per square centimeter per minute was the flow they suggested and we have been using approximately 30 milliliters per square centimeter of floor area per minute . We think that this larger quantity may be marginal and is something that we can discuss later .

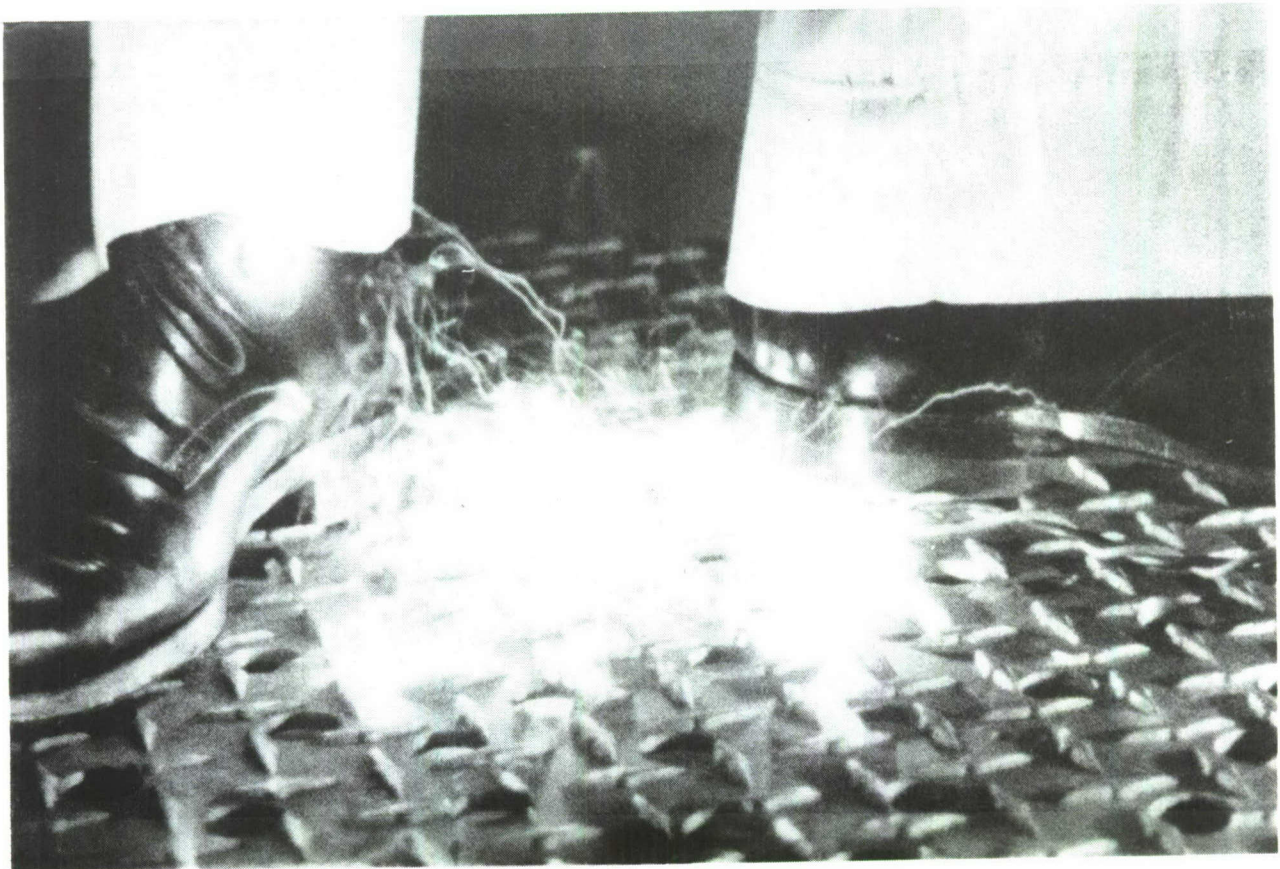
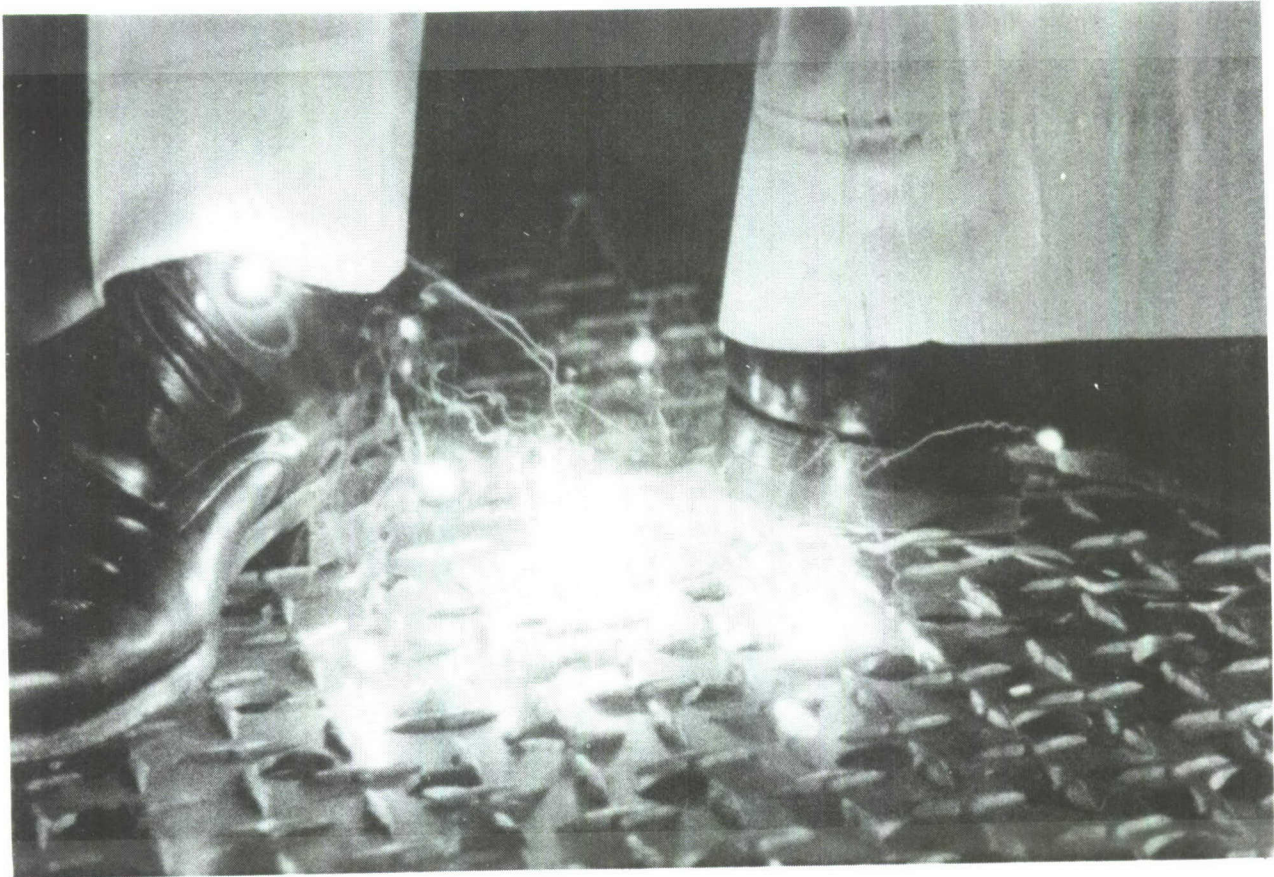
I would like to , at this time , show a short film of a wire shorting into an aluminum plate . Earlier you saw wires that had arced against the aluminum floor for one tenth of a second , another that had arced











for one half second and the wire from the chamber that had arced for a time period somewhere in between those two, if the intensity of burning is an indication of the length of time. There were a number of us on the Board of Investigation who felt that it was quite impractical for a spark of this nature and source to have been the source of this fire. There had been some suggestions, and we looked into these possibilities quite seriously of static discharges and a combustible atmosphere. We also considered quite carefully whether or not this might have been a dust fire and we are quite sure that it was not a dust fire. This short film will give you some idea of how far molten bits of metal can be propelled from an arc. The film shows a foot stepping on a 110 volt AC wire identical to that used in the lamp in the chamber. The floor plate is the non-skid aluminum floor plate from the experimental chamber. On some occasions these sparks have been propelled in the neighborhood of sixteen to eighteen inches. This was done at one atmosphere of air. Sometimes it was quite difficult to get the spark and sometimes it was very easy to step and get the spark. Notice this spark, for example, falling a little short of the trouser leg. Now notice this one that is coming up. It is now on the trouser leg and is now falling off just above the shoe. This indicated to us that the fire could indeed have started in this manner.

A REVIEW OF THE NAVY CHAMBER FIRE SAFETY PROGRAM

Lieutenant Commander John V. Harter, USN
US Navy Experimental Diving Unit
Washington Navy Yard
Washington DC

I would like to briefly describe the Navy's interest in the flammability problem in the hyperbaric chamber, the reason for it, show a few slides of the results of the fire that occurred at the US Navy Experimental Diving Unit on February 16 two years ago, mention the program that we laid out after that, and then introduce Dr Gerhard Cook from the Union Carbide Corp, Linde Division in Tonawanda, who is the Navy contractor studying the flammability aspects of different atmospheres and determining the flammability characteristics of various materials that have been used in chambers. The Navy's deep sea diving program includes an ASR diving system being designed by the Deep Submergence System Project. Most people know this project as the Man in the Sea Program, which includes Sea Lab III scheduled for commencement next year. This program will eventually provide ten ships that will each have two large saturation chambers on board with a transport vehicle to lower the divers to the bottom. The ATS diving system is designed for a fleet salvage tug. It has a small topside chamber and a vehicle to lower the divers to the bottom. In both cases extensive periods of chamber occupation are anticipated.

The ASR system will use the saturation diving concept with the oxygen percentage low in most cases. In order to provide a constant partial pressure of oxygen in the chamber the oxygen percentage is decreased during descent and at some point we enter an atmosphere of noncombustibility. However in the ATS diving system, the salvage tug system, we anticipate that most of the diving will be done with the diver breathing a mixed gas atmosphere from the breathing apparatus and the background gas will consist of compressed air. It is in the area of compressed air we are most concerned for fire safety.

This is a diagram of the chamber system at the Navy Experimental Diving Unit in Washington. The Experimental Diving Unit has two chambers, configured in this manner, and the diving school, which is located in the same building, has two additional ones. (See Figure 1) We have a hatch between the wet pot and the igloo, and can place the diver in the water, close this hatch, and make excursion dives from saturations depth in the complex. During the dive in which the fire occurred, two divers had exited from the wet pot and had transferred into the chamber at 92 feet. We had a mixture of 28% oxygen, the remainder, nitrogen and helium, in the chamber when the fire occurred. The cause of the fire was traced to this carbon dioxide filter unit, which had been developed by the Naval Research Lab some time in the past for use in submarines. (See Figure 2.) The gas flows down through the

FIGURE 1.
DIVING FACILITIES
AT

U. S. NAVY EXPERIMENTAL DIVING UNIT
WASHINGTON NAVY YARD
WASHINGTON, D. C.

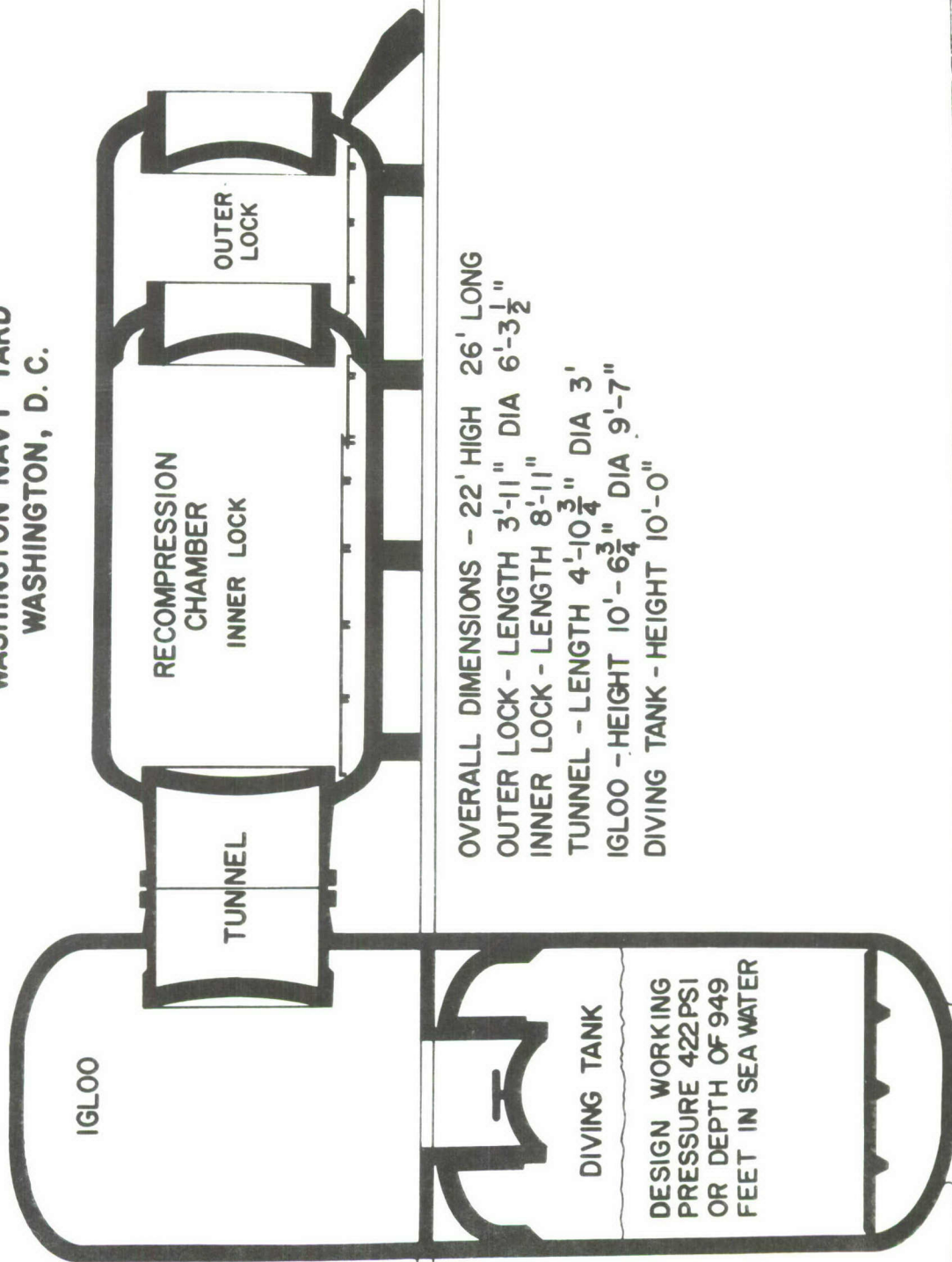




Figure 2 CO₂ Filter Unit

various canisters and up through the filter element. Notice in the figure that there is no insulation left on the wire. We determined that the motor had a starting switch which stuck in the open position, overheated and caused the wire and filter to burn. The filter which came with this unit was originally intended for use as a jet fuel filter and one of the tests performed during production was to dip the filter in kerosene. Additional filters that were taken from the shelf and tested had a high content of kerosene. It was well established that this was the cause of the fire.

Figure 3 is a picture of the chamber before the dive. Please note the oxygen inhalators, toilet paper, the plastic box with instrumentation connected and the light globe. In Figure 4 notice that all the fabric and rubber was burned from the inhalators. The light globes also burst. We felt, through data taken by the Naval Research Lab, that we had about 1400°F in the chamber at the peak of the fire. Figure 5 shows a lot of debris. This is the remains of a mattress and the scrubber unit. It appears that the entire interior was burned out, however, the paint was damaged only in one small area. We found that due to the mass of the steel chamber walls the heat was taken away before ignition occurred. We subsequently used a propane torch at atmospheric pressure and could not get the paint to blister.

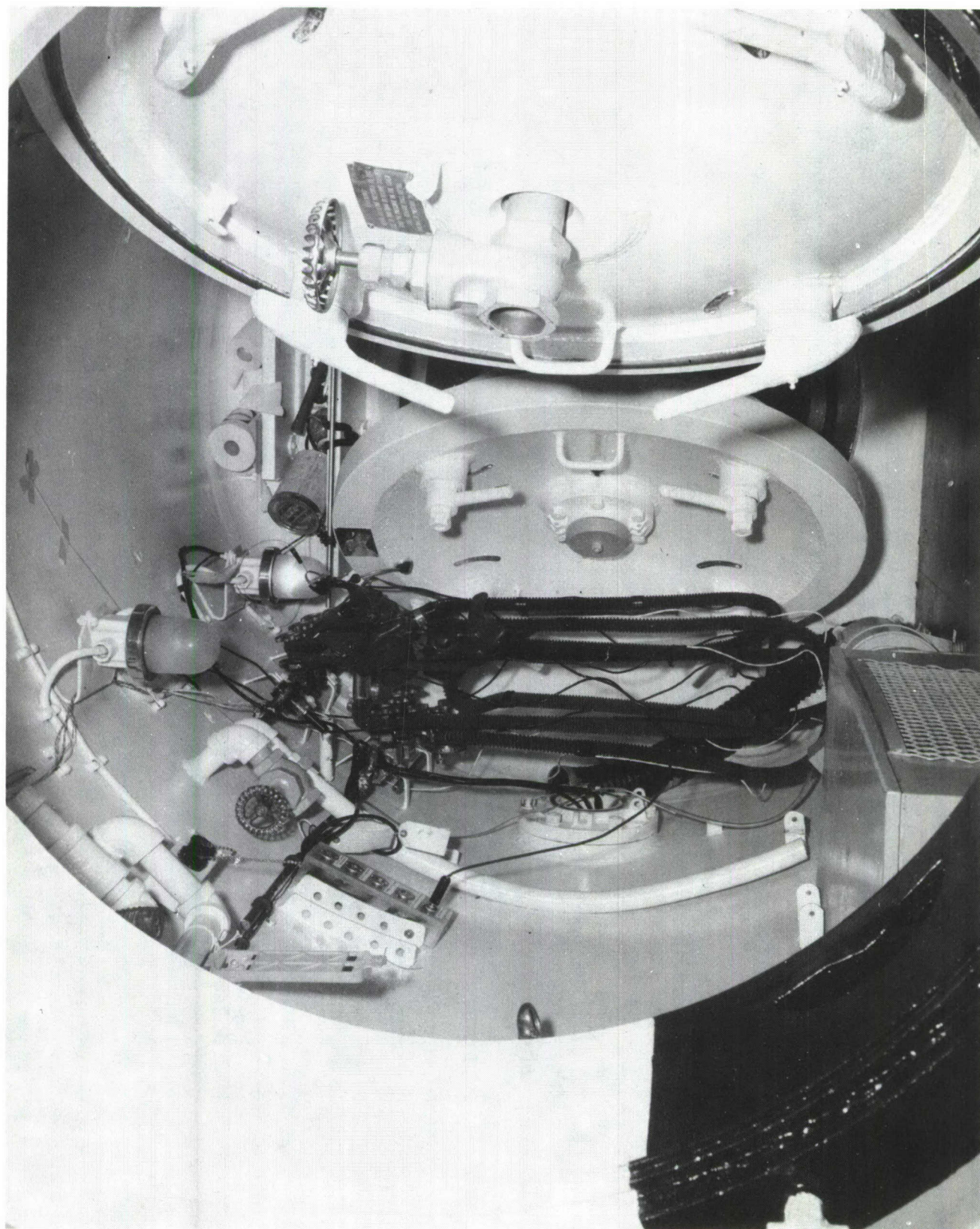


Figure 3 Hyperbaric Chamber Prior to Fire

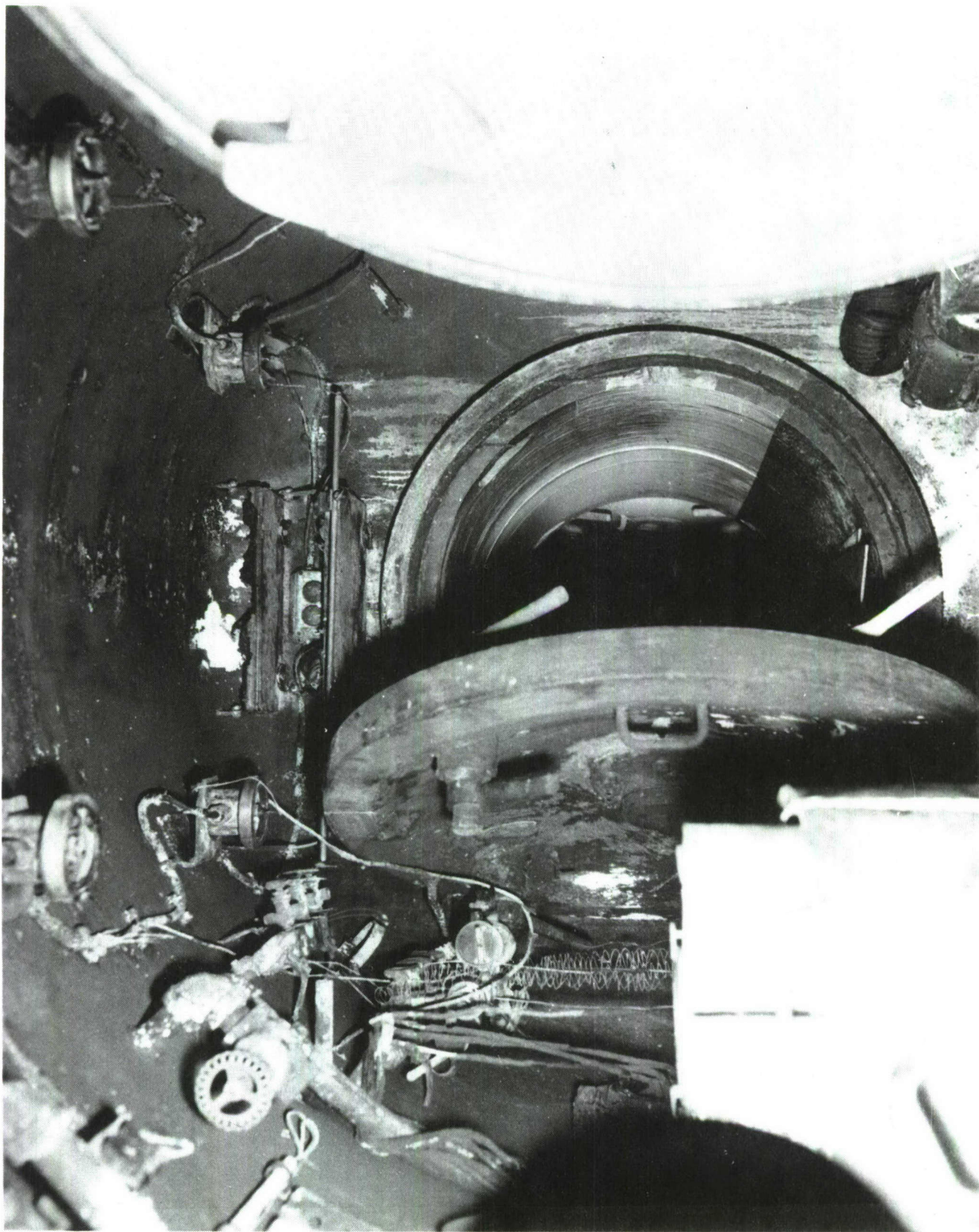


Figure 4 Hyperbaric Chamber Subsequent to Fire

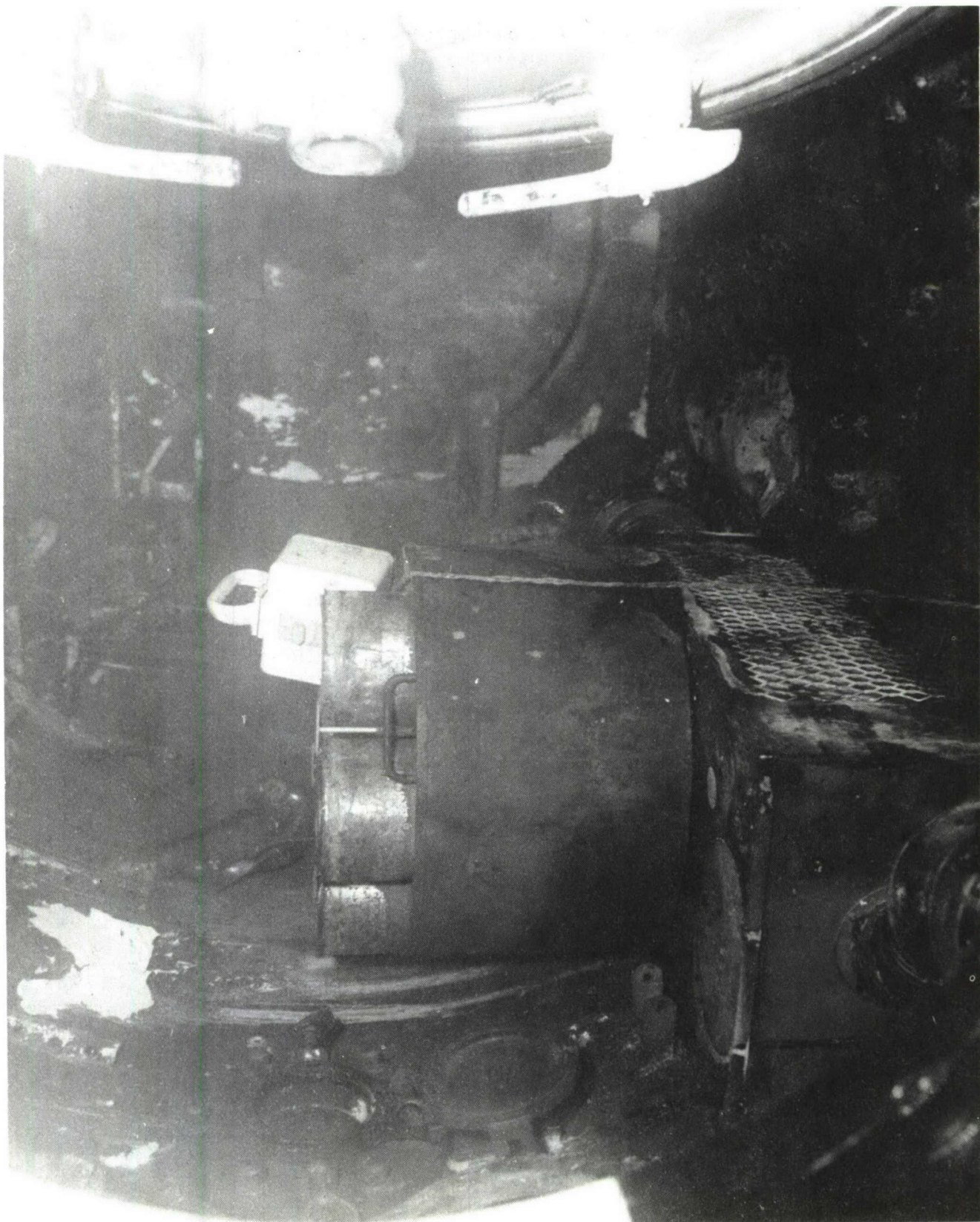


Figure 5 Hyperbaric Chamber Subsequent to Fire

Dr Cook of Linde Laboratories made some tests and verified that in 100% oxygen the paint film would not burn with 3/8 inch steel behind it. Figure 6 shows the water bucket that had been in the chamber as a fire protection system and the zinc galvanize was melted from the upper part of the bucket. The flash proof mattress cover did not burn, however, it was partially worn. The fire apparently propagated through and burned the stuffing out.

We laid out a program at the Navy Diving Unit to essentially remove the sources of ignition and remove flammable material. We now operate in lower partial pressures of oxygen. In the area where we have to work with an air background we do not transfer the diver from the water to the chamber at depths beyond 200 feet. We had hoped to provide extinguishing systems. Of the goals that were set out two years ago, we have made progress in locating what we feel is an adequate mattress made from a Pittsburgh Plate Glass material called textrafluff; we have designed an up to date electrical system, and located Nomex clothing for use by the divers in the chamber. In the area that this conference points to today, in fire extinguishment, no apparent progress has been made.

I would now like to introduce Dr Cook who has been under contract to the Office of Naval Research and the Experimental Diving

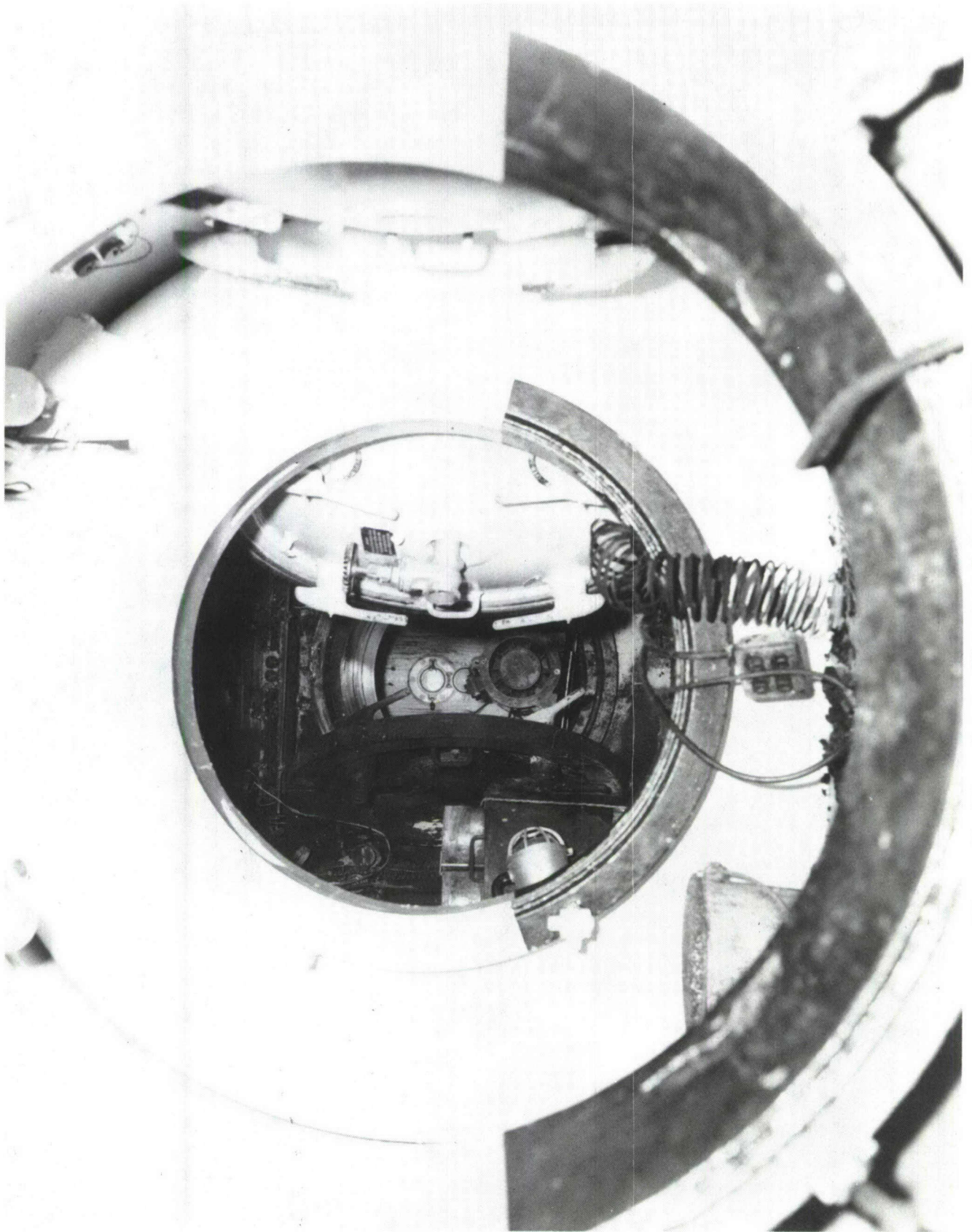


Figure 6 Hyperbaric Chamber Subsequent to Fire

Unit for a year and is now starting his second year of study of the flammability problem. He will give you a brief on some of his findings.

COMBUSTION SAFETY IN DIVING ATMOSPHERES

Dr Gerhard A. Cook
Union Carbide Corporation
Linde Division Research Laboratory
Tonawanda New York

Abstract of talk given at Brooks Air Force Base, San Antonio, Texas, on May 23, 1967.

I. Introduction

For the past year a group in the Research Laboratory (Tonawanda, New York) of the Linde Division of Union Carbide Corporation has been working under a US Navy contract funded about equally by the Office of Naval Research and the Ship Systems Command, entitled "Combustion Safety in Diving Atmospheres." The technical monitor for this contract is Lieutenant Commander John V. Harter of the US Navy Experimental Diving Unit, Building 214, Washington Navy Yard, Washington DC.

A report (1) on the first year's work under the contract not only gives our experimental results, but also includes a review of the literature and a discussion of many of the problems connected with the subject of fire hazards in enclosed spaces. The report is of interest to the Air Force, to NASA, and to all hospitals in which oxygen enriched and/or hyperbaric atmospheres are used for therapeutic purposes, as well as to the Navy and to all those interested in deep diving.

The following information from our work is of particular interest in connection with this meeting.

II. Burning Rates of Paper Strips in Nitrogen-Oxygen and in Helium-Oxygen Mixtures

Figures 1 and 2 show burning rates for strips of filter paper 6 mm wide by 155 mm long, held at an angle of 45° inside a stainless steel pressure vessel. Total pressures are given in atmospheres absolute (AA) and in feet of sea water (FSW). Burning rates for increasing total pressure are given along the curves (labeled in mole-% oxygen) which start at the origin and extend upwards and to the right. The other curves, roughly orthogonal to the first curves, show the effect on burning rate of dilution (by either nitrogen or helium) of the oxygen while the partial pressure of oxygen is kept constant.

The principal conclusion to be drawn from Figures 1 and 2 is that the combustion rate for any given total pressure goes up extremely rapidly as the partial pressure of oxygen is increased. For example, at a total pressure of 1 atmosphere absolute the burning rate of the paper strips in oxygen-nitrogen mixtures (Figure 1) went from about 1.0 cm/sec at a partial pressure of 0.21 atm O_2 to 4.3 cm/sec at 1 atm of essentially pure oxygen.

Figure 3 shows the ratios of burning rates obtained with strips of paper held at a 45° angle in helium-oxygen mixtures to the burning

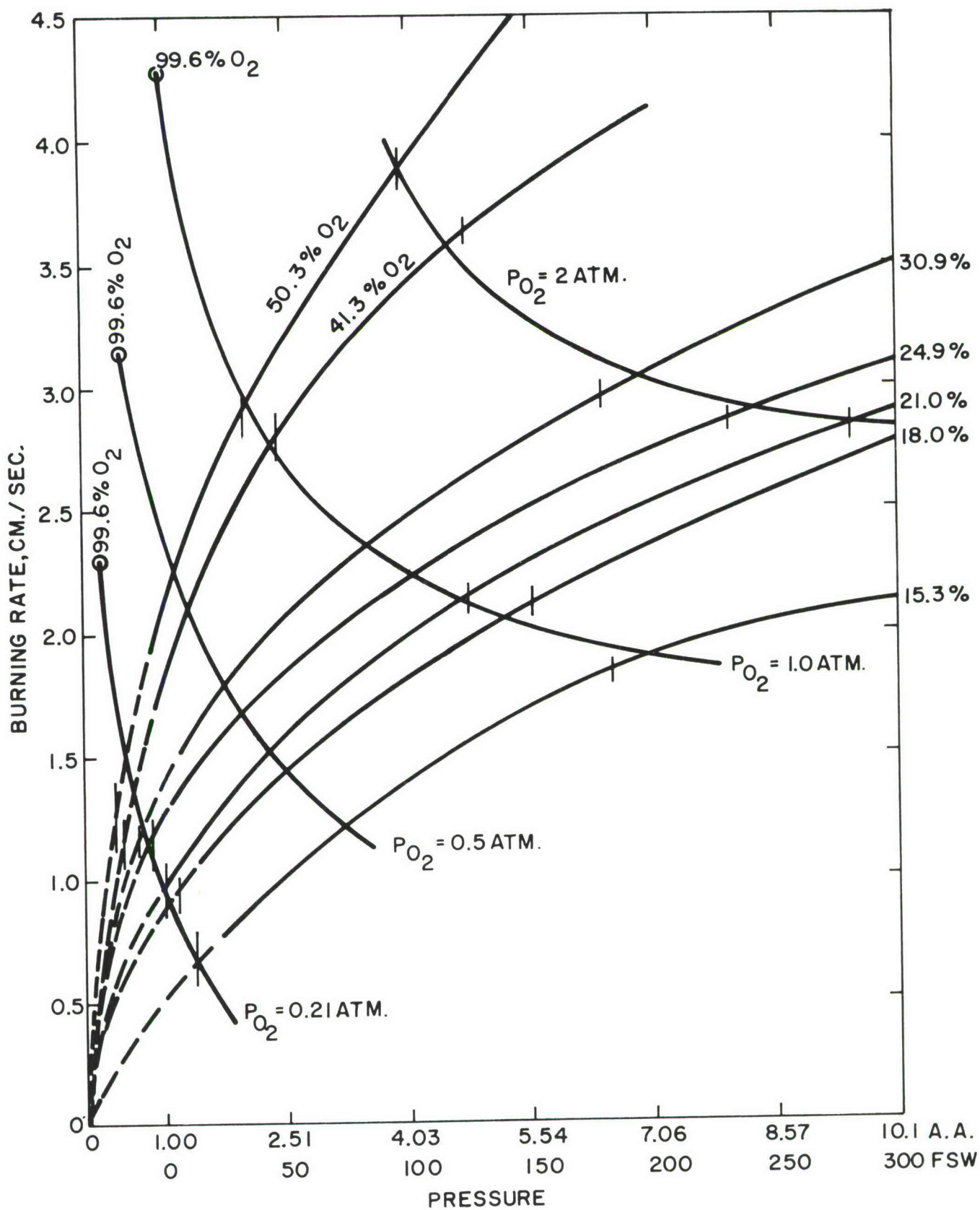


Fig. 1 Union Carbide-Linde Experimental Results for Nitrogen-Oxygen Mixtures

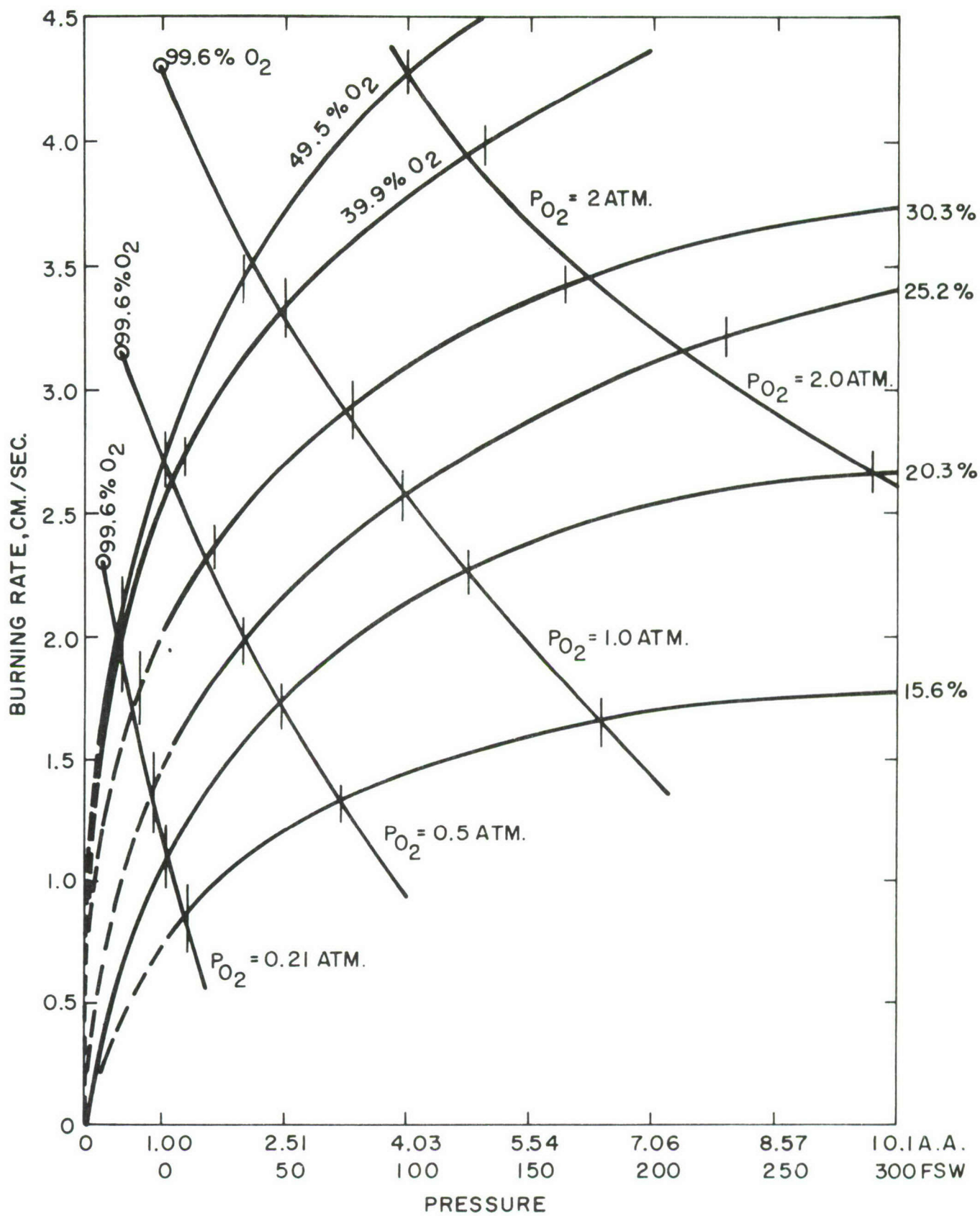


Fig. 2 Union Carbide-Linde Experimental Results for Helium-Oxygen Mixtures

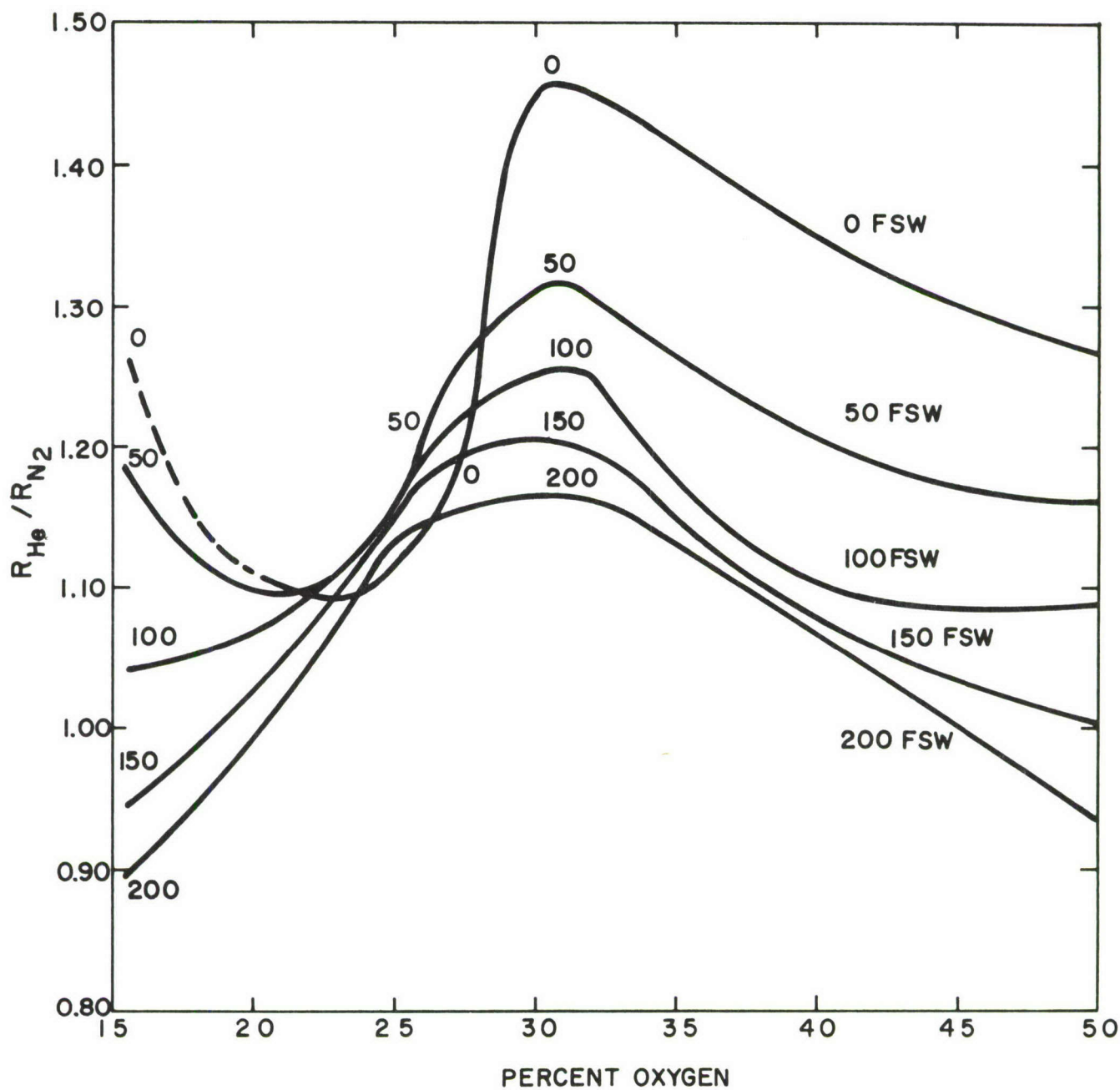


Figure 3. Relative effect of helium and nitrogen as oxygen diluents on the rate of combustion of paper strips at an angle of 45°

Fig. 3

rates in nitrogen-oxygen mixtures under corresponding conditions (of pressure, etc). It is seen that under most conditions, the paper strips burned more rapidly when the oxygen was diluted by helium than by nitrogen, the conditions being the same.

III. Exhibition of Samples of Materials Having a High Degree of Flame Resistance

Well over sixty types of materials have been tested by us for flame resistance. In the absence of any standard classification scheme, we have tentatively classed each of these materials in one of 10 classes with increasing fire resistance, as follows:

Class 0. Burns readily in air at atmospheric pressure.

Class 1. Has an appreciably higher ignition temperature and/or burns at an appreciably lower rate in air at 1 atmosphere absolute pressure than cotton cloth or paper. An example of a Class 1 material is wool.

Class 2. Nonflammable or self-extinguishing in air at one atmosphere absolute pressure.

Class 3. Self-extinguishing or burns slowly in air at a pressure of 100 fsw (4.03 atmospheres absolute).

Class 4. Self-extinguishing or burns slowly in air at a pressure of 200 fsw (7.06 atmospheres absolute).

Class 5. Is self-extinguishing or burns slowly in a mixture of

25% oxygen and 75% nitrogen at a pressure of 1 atmosphere absolute.

Class 6. Self-extinguishing or burns slowly in a mixture of 30% oxygen and 70% nitrogen at a pressure of 1 atmosphere absolute.

Class 7. Self-extinguishing or burns slowly in a mixture of 40% oxygen and 60% nitrogen at a pressure of 1 atmosphere absolute.

Class 8. Self-extinguishing or burns slowly in a mixture of 50% oxygen and 50% nitrogen at a pressure of 1 atmosphere absolute.

Class 9. Completely nonflammable, even in 100% oxygen at 1 atmosphere absolute pressure; e.g., beta fiberglass.

Samples of the following materials were shown at the meeting:

Cloth Fabrics

Beta Fiberglas	Owens-Corning	
Experimental Asbestos	Uniroyal	Class 9
Fiberfrax	Carborundum	
Teflon, both brown and white	DuPont	
Teflon-coated glass cloth	DuPont	Class 8
Wonder Shield - plain	J P Stevens	Class 5

Rubber

Carboxy nitroso rubber terpolymer	Reaction Motors Division of Thiokol	Class 9
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Gasket Material

Vitron A	DuPont	Class 6
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Insulation for Electrical Wires

Kapton	DuPont	Class 9
WTE	IT&T	Class 8

Film

Kapton (3 mils or more thick)	DuPont	Class 7
Kapton (1 mil thick)	DuPont	Class 5

IV. Burning of Paint

We have confirmed the observation made by Harter (2) that a thin coat of paint on steel does not burn in a fire. The paint may char if heated sufficiently, but it does not burn. A similar observation has been made by Huggett (3) for a film of Scotch tape stuck on 1/8-inch thick aluminum plate.

V. References

(1) Cook, Gerhard A., Robert E. Meierer, and Bruce M. Shields, "Screening of Flame Resistant Materials and Comparison of Helium with Nitrogen for Use in Diving Atmospheres," first annual report on ONR Contract No N00014-66-C0149, "Combustion Safety in Diving Atmospheres," March 31, 1967. This report is No AD-651583, obtainable from either the Defense Documentation Center, Cameron Station, Alexandria, Virginia 22314, or from the Clearinghouse for Federal Scientific and Technical Information, Springfield, Virginia 22151.

(2) Harter, John V. (US Navy Experimental Diving Unit, Washington,

DC), "Fire at High Pressure," paper presented at the Third Symposium on Underwater Physiology held in March, 1966, at the National Academy of Sciences, Washington, DC.

(3) Huggett, Clayton, G. von Elbe, W. Haggerty, and J. Grossman, "The Effects of 100% Oxygen at Reduced Pressure on the Ignitibility and Combustibility of Materials," SAM-TR-65-78, December 1965.

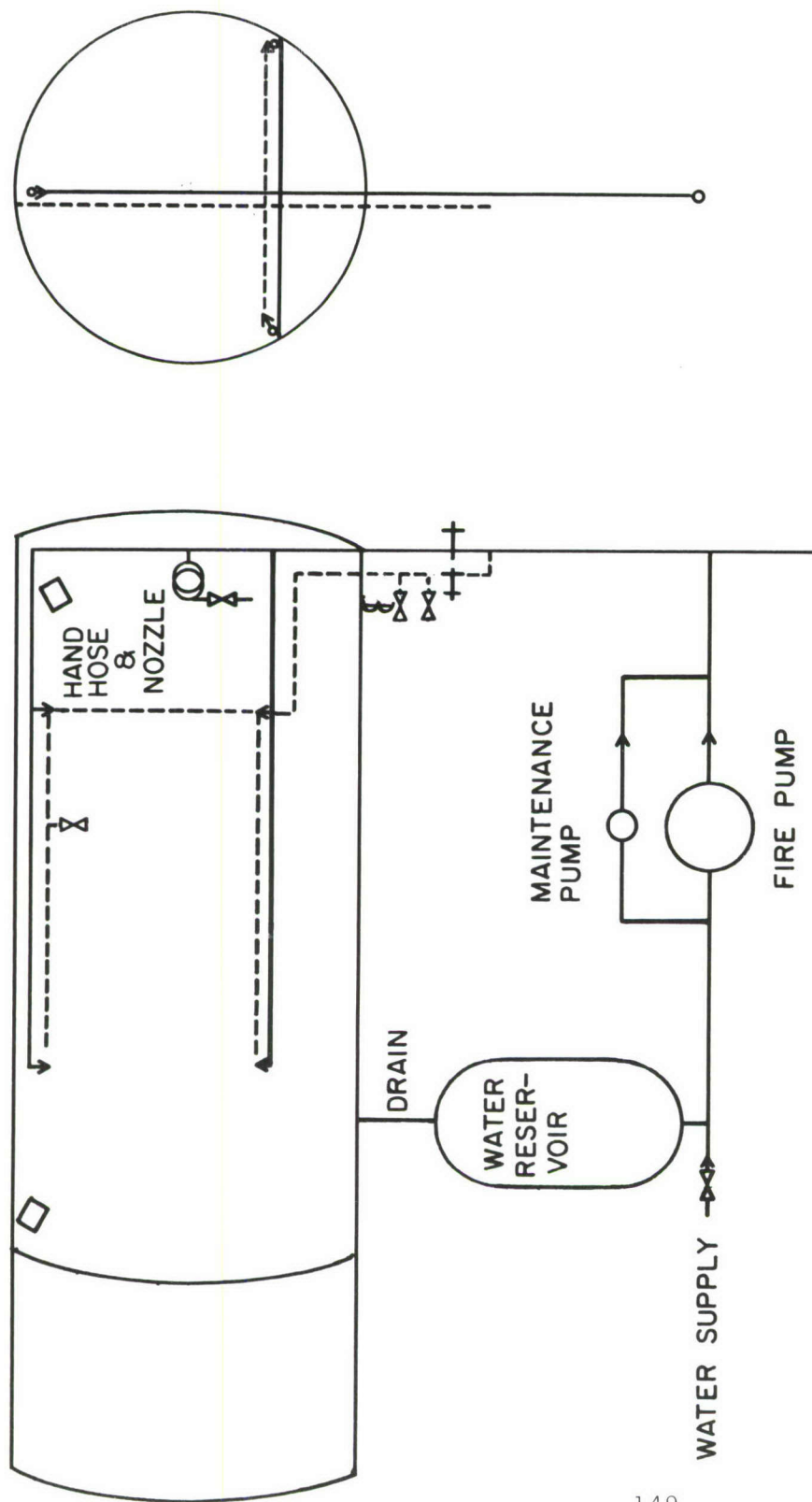
HAZARDS ASSESSMENT AND PROTECTIVE CLOTHING REQUIREMENTS

Mr Thomas E. Goonan
General Engineer
Veterans Administration
Washington DC

As District Fire Protection Engineer I was charged with investigating the cause of the fire at the Navy Experimental Diving Unit and determining measures to prevent a further recurrence. The first part of the task was relatively simple and we concluded our work in several weeks. The second part, to prevent recurrence, I am still working on although I left the Navy and am now with VA. Today's conference, of course, is aimed directly at that problem.

I had responsibility in the Navy for the design of protective measures. Some of these measures have been carried out. Some of them are only being seen as the first approximation today in the test within the chamber. This has been a slow process and I am sorry that we are not a lot further ahead than we are but as you realize it takes a lot of money and determination from the "head shed" in order to get a thing like this started. I made a few proposals over the past couple of years for protection. One of them is being partially done today. Reference Figure 1.

This represents a simple hyperbaric chamber with an outer lock and I have indicated sprinkler protection inside. The heads indicated



- ▲ PILOT OPERATED SPRINKLER HEAD
- HYDRAULICALLY SIZED SPRINKLER PIPE
- - - 1/4" PILOT LINE
- + OS & Y VALVE
- CHECK VALVE
- ▲ QUICK OPENING VALVE
- ▲ OPERATING SOLENOID
- PUMP
- ULTRAVIOLET DETECTOR

FIGURE 1. SCHEMATIC OF FIRE PROTECTION SYSTEM FOR HYPERBARIC CHAMBER

are the pilot operated heads that have been installed in the chamber here. You saw a chamber so equipped with three lines of sprinklers overhead. What I propose is a single line on top and a line on each side at floor level to project up. As you have probably seen in some of the fire test films, burning occurs in shaded areas under sprinkler protection and to reach these areas we need some kind of projection like this. It is relatively simple to sprinkle a hypobaric chamber at less than one atmosphere. When we pressurize above one atmosphere we run into other problems. One is the size of the droplet projected by the sprinkler head. As you increase the pressure of the distributing system you are going to reduce the size of the drop and, to some extent, the amount of carry, the radius of distribution, of the water. The thickness of the atmosphere increasing also tends to reduce the spread of the water so that to maintain a relatively constant pressure differential between the sprinkler head and the chamber I have indicated a reservoir which is pressurized from the chamber, a centrifugal pump which has a fixed head pressure so that the pressure difference between the pump intake and discharge, or the pressure difference between the sprinkler head and the chamber, is always the same no matter what the pressure is. We can do it this way without a lot of complicated controls. I have also indicated a hand hose. I think this is important. Most of these chamber fires develop too rapidly for a hand operated hose to have

an important effect, but I think it is very bad when we have injuries in these chambers and the people inside have no means of defense whatsoever.

I do not think I can add anything at all about protective clothing after the excellent presentation you just had. I think there is a very clear indication, and I don't think it can be emphasized too much, that more than a single layer of clothing presents serious problems and that any clothing worn should be tight fitting. I would like to point out that there is no electrical equipment that is approved for use in either high oxygen atmospheres or in pressures other than sea level. There is electrical equipment that can be used, but there is no assurance except the tests that you yourself make, that prove it safe to be used in the atmosphere in which you need it. To the greatest extent possible, electrical equipment should be removed to the outside.

I think the suggestion or mandate to make these chambers so lean in combustibility that there is no chance for a fire to start is a commendable goal, but it is only a goal. I have some responsibility for hospital chambers and, gentlemen, if a doctor wants to carry something into a hospital chamber, he is going to carry it in. It does not make any difference what you say about it--it is going to

be there, whether it is electrical equipment, clothing, instruments of any kind, medicines or gases. We can only go so far in fire prevention and then we have to provide fire protection. I think one of the great fire prevention measures is the provision of fire protection. You would be surprised how much more attention a piece of equipment gets in the matter of fire prevention and inspection if it has a protective system.

I think my most important proposal today for hyperbaric chambers is the maintenance of 3 lbs partial pressure of oxygen in the atmosphere so far as is possible. Figure 2 is a little chart I made up last night. We have partial pressures plotted against atmospheric pressures. The 3 psi line is basically our life support requirement of oxygen. The shaded portion is the amount of oxygen that we provide when we pressurize with compressed air. This is oxygen that does not particularly contribute to life support but it does contribute considerably to a fire. The 45° line represents the total pressure of compressed air. Point 3 on this chart represents the conditions of the diving chamber fire--a partial pressure of approximately 15.3 psi of oxygen in a total pressure of about 60.1 psi absolute. Point 1 represents the Apollo pad fire, 16 psi of pure oxygen. The fire in the Brooks chamber was about 7 psi of pure oxygen. There are several other fires that had 5 psi of

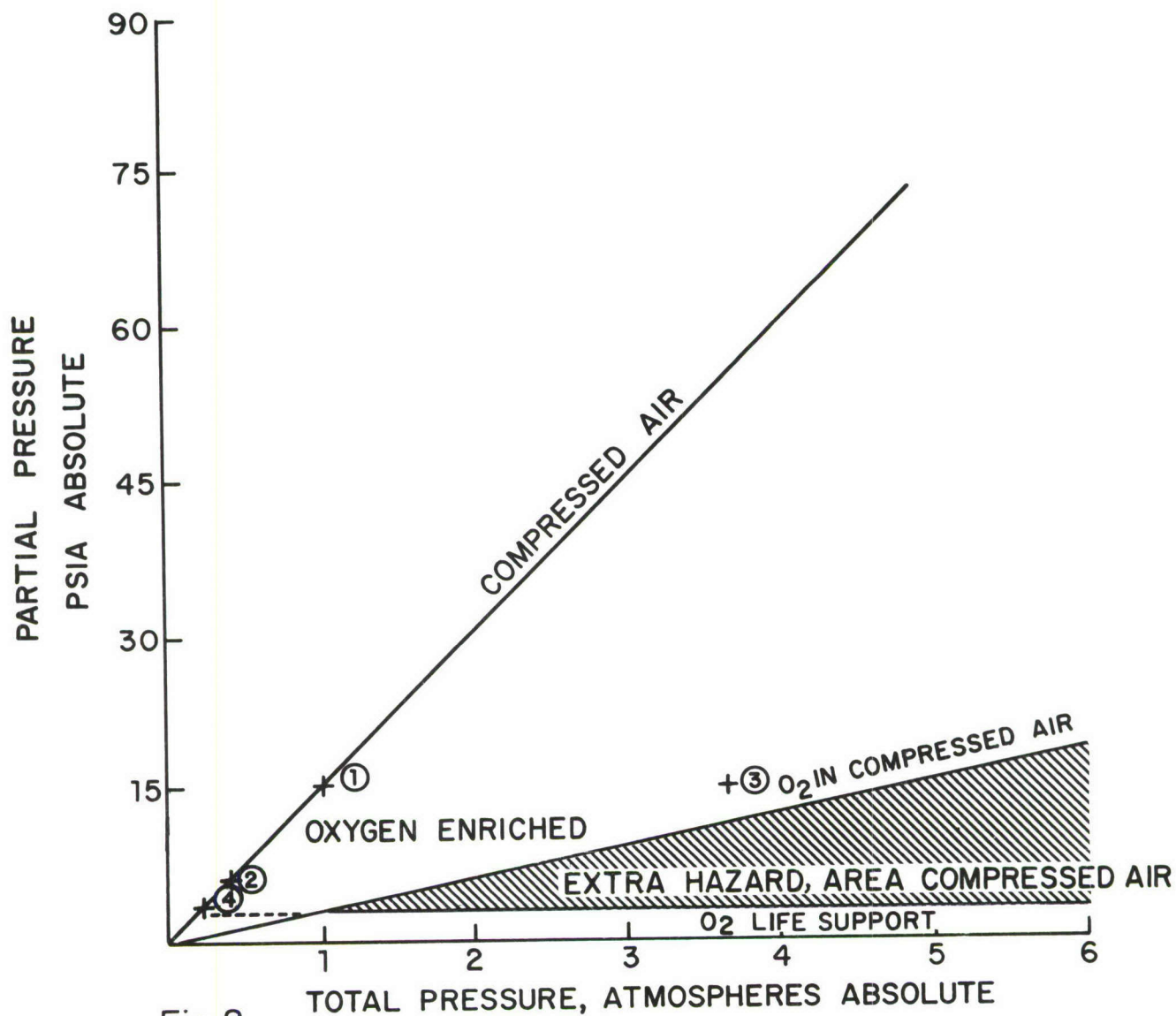


Fig.2

- 1 APOLLO PAD FIRE 1/27/67
- 2 BROOKS AFB FIRE 1/30/67
- 3 NAVY DIVING FIRE 2/16/65
- 4 USAF CHAMBER FIRE 9/9/62
- AND
- US NAVY ALT. FIRE 11/7/62

oxygen--all above the 3 psi life support line. Now, generally, the fire hazards of an atmosphere are proportional to the amount that you exceed this life support line. When you are operating above this life support line you have a higher hazard than is necessary, and in a very general way, a hazard that is greater than in normal atmosphere. As you have heard, some inert gases will tend to depress the hazard somewhat, but generally speaking, the further you get above this line the greater the hazard is. We have a body of experience that is based upon what a fire will do at normal atmosphere and when you exceed this line you get into these special hazard flash fires, fires in materials that are normally noncombustible. So, as a rough measure of what the problem is, determine the partial pressure of oxygen in your atmosphere and see how far you are above 3 psi. This will give you a very rough gauge of what the problem is. I am very glad to have been able to come here today and I thank you for your attention.

FURTHER STUDIES ON THE PROBLEMS OF FIRE IN ARTIFICIAL GAS ENVIRONMENTS

Squadron Leader D. M. Denison, RAF
Royal Air Force Institute of Aviation Medicine
Farnborough Hants England

Thank you Colonel Swan for inviting me here. I think this morning we have seen, in the Freon bomb, a very important advance in the control of fire, and I congratulate Captain Carter very much for his work in this field. Now as Colonel Swan very generously indicated we did some work on the subject two or three years ago. What we did was to carry out some experiments on clothing fires on a human scale. These were done because at that time there was no useful information on the subject in human terms, and the experiments did uncover some unsuspected and important facts about the problem, in particular:

1. They showed that fire could pass over the surface of clothing as a flash fire; this was propagated in the nap and it was capable of igniting the material at many points almost simultaneously. The effect of this was to increase the burning rate many fold.

2. Some flame proofing treatments prevented the appearance of this nap propagation.

3. A similar flash fire could pass over the surface of dead pigs, even if they were clothed in proofed material. By analogy, they could also pass over the surface of human beings.

4. Such fires could not pass underneath tight clothing.

5. Ordinary water sprays were incapable of controlling such fires.

6. It was possible to design a water sprinkler system that could control the fires if attention was paid to obtaining an evenly dense spray in all spatial dimensions. However, because of the accelerated time course of these fires, fatal damage could occur within 5 seconds, a manually operated system would be ineffective and the extinguishing system would have to be automated. Sergeant Pignatelli, while he was with us, did design and build a successful automatic fire sensing and suppression system of this sort (Pignatelli, 1965).

These early experiments then had brought to light the problem of flash fires and had crudely indicated methods of controlling them. They had also shown that pig skin, and one assumed human skin, could support flash fires, but the relevance of the pig experiments was debatable. This is where our experiments rested at that time. Then there were the Apollo and San Antonio fires which as far as one could tell from the newspaper reports, followed exactly the pattern predicted from these early experiments. These accidents prompted us to resume work on fire suppression with three objectives in mind:

1. To obtain a more precise idea of the nature of flash fires.
2. To compare the values of nitrogen and helium as inert

diluents from the fire viewpoint.

3. To observe the behavior of human skin in such fires.

(Figure 1) The experiments, 125 of them in all, were conducted as before, that is to say that on each occasion an unproofed denim overall, mounted on a brass dummy was suspended in the center of a chamber that was sealed and which could be filled with any desired gas mixture at pressures up to one atmosphere. The overalls could be ignited by closing a 24 volt circuit that included a fixed length of nichrome wire sewn into the pockets of the overall. Four observations were made on each occasion.

1. The time interval between closing the ignition circuit and the first appearance of flame was noted. This is a reciprocal measure of the energy required to ignite the system.

2. We arbitrarily classified fires into seven grades on the basis of their flash fire characteristics and each experimental fire was assigned a grade number.

3. The time interval between the first appearance of fire and the moment when 50 percent of the dummy was obscured by flame was noted.

4. Similarly and lastly, the time interval between the first appearance of fire and the first moment when the dummy was totally obscured by flame was also noted.

The results of these experiments are a matter of detail and there

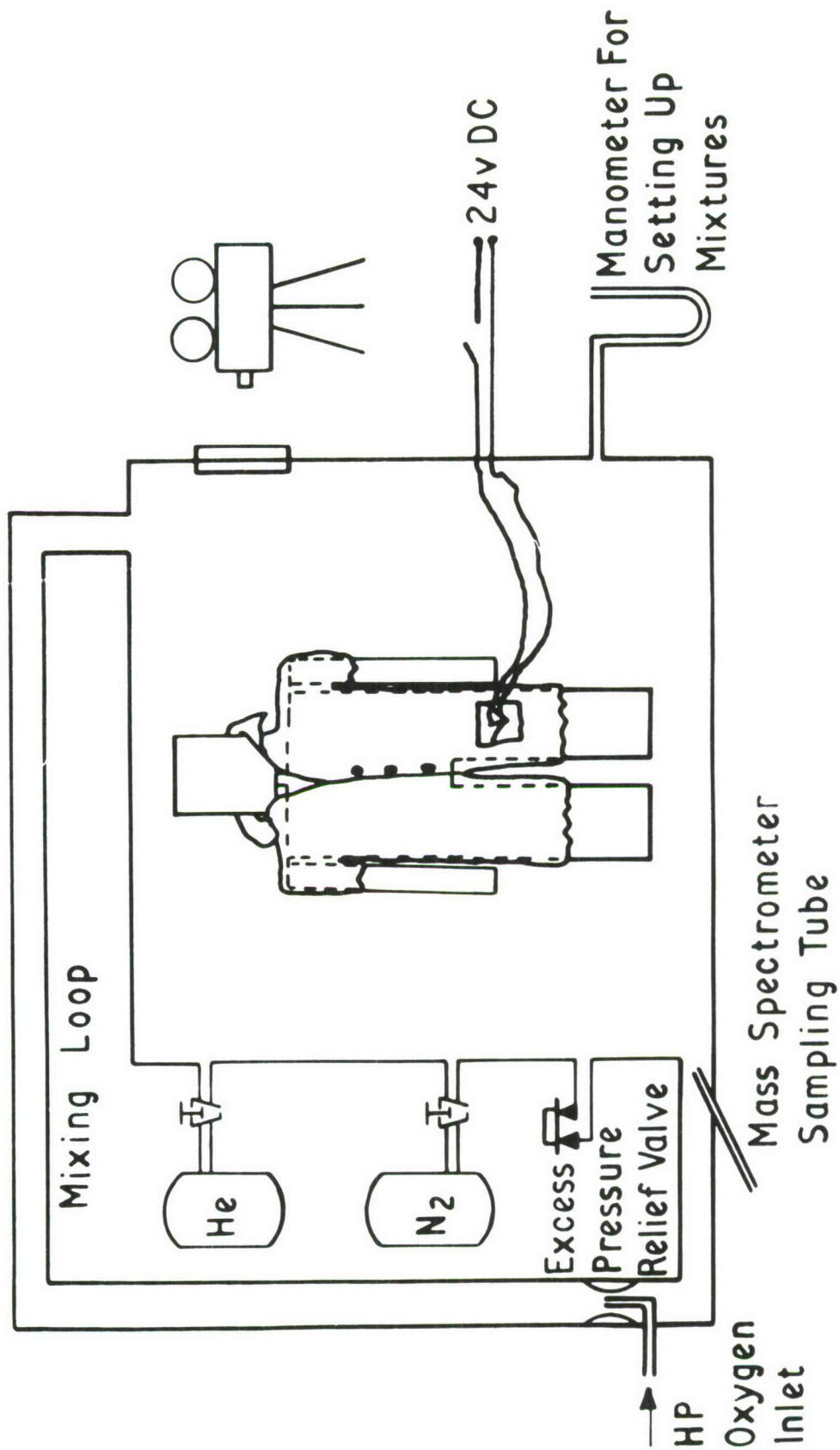


FIGURE 1. A SCHEMATIC SUMMARY OF THE APPARATUS

is not time to discuss them here now, however they have been written up (Denison and Tonkin, 1967) and I have brought copies of our report with me and they are available for anybody who would like them. What I would like to do now is to explain in what way the results have altered our understanding of these problems.

(Figure 2) Firstly, what have we learned about the nature of flash fires. All materials show an increase in ignitability with pO_2 . For fire to spread, it is necessary for fire in one area to raise an adjacent area to its ignition temperature, so this is equally true of burning rate. The results suggest that it is reasonable although naive to look upon clothing fabric as a sandwich of a layer bulk material between two layers of nap. Both the nap and the bulk fabric can be regarded as materials in the sense of this graph, but their characteristics vary. At low partial pressures of oxygen the nap is much less ignitable than the bulk material, however, as the partial pressure of oxygen increases the ignitability of the nap rises more steeply than that of the bulk material. We know that the spread of fire in the nap is predominantly by radiation; each hair has to raise an adjacent hair to its ignition temperature for a flash fire to propagate and this basis is almost independent of convective forces. On the other hand, fires in the bulk fabric spread mainly by convection and are little affected by other forces. These facts are sufficient to predict the pattern of fires one would see if

A SIMPLE MODEL OF "FLASH FIRES" ON CLOTHING (almost hypothetical)

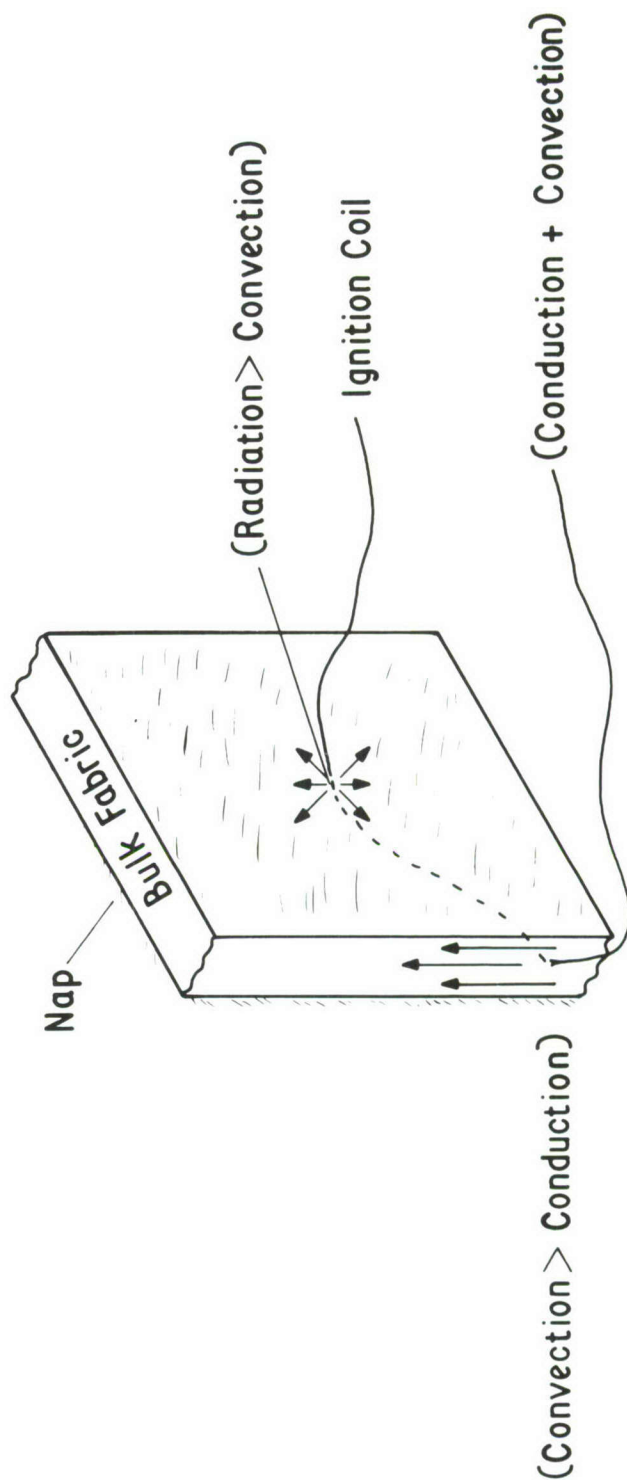
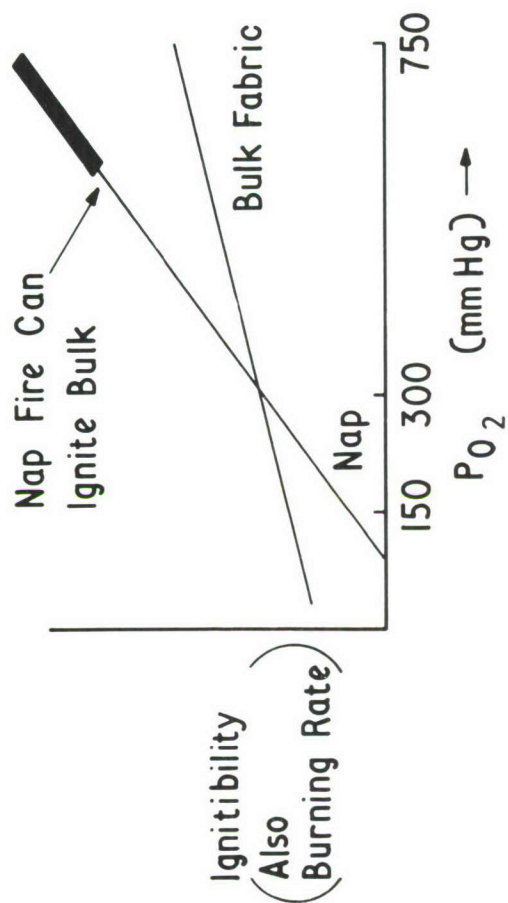


FIGURE 2

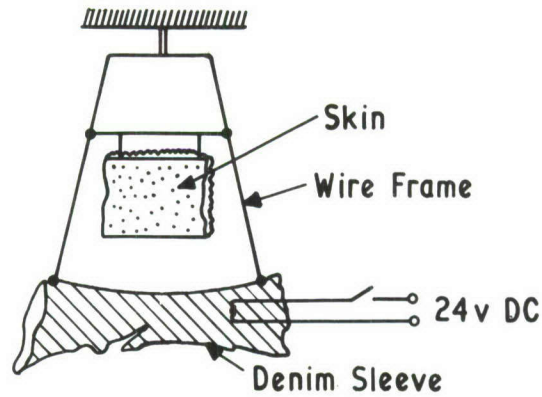
the surrounding pO_2 was progressively raised. At low pO_2 s there would be a unifocal fire confined to the bulk cloth and spreading predominantly upward by convection. As the pO_2 rises there comes a level at which local nap fires appear in areas heated by convection. At a somewhat higher oxygen pressure, the point of intersection in Figure 2, nap fires and bulk fires appear simultaneously and nap fires will have sufficient energy to ignite the bulk of the cloth. At higher oxygen pressures, nap fires will precede the bulk fire and ignite the bulk cloth with increasing ease.

Now let us turn to the comparative effects of nitrogen and helium. Nitrogen has much the same thermal properties as oxygen and one would anticipate that its main effect on fires would be by opposing the development of convective currents and reducing the inflow of fresh oxygen to the fire, so one would expect that it would have very little effect upon the temperature of the ignition coil and if anything would tend to raise it and similarly that of the ignition site. It would have little impression on the spread of nap fires, but it would have a marked effect on the convective spread of bulk fires once it was present in any quantity. Helium, in contrast, has a high thermal conductivity but a low density and so is a less effective brake to convection; these two influences act together to reduce the temperature of the ignition coil and of the ignition site, so helium prolongs ignition time

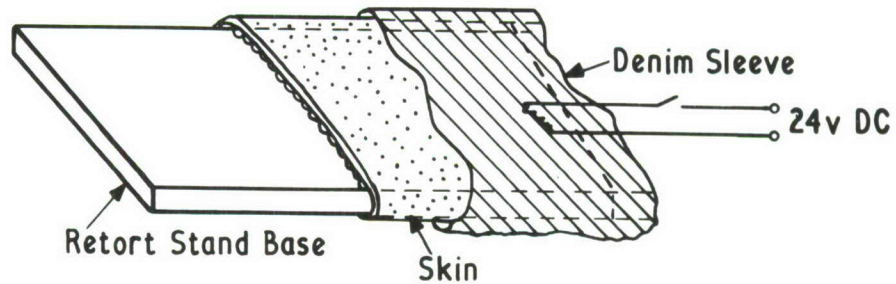
considerably more than nitrogen in equal amounts. Similarly helium is much more effective at suppressing nap fires. However, once a bulk fire has been established in a normal gravitational field, helium is less effective than nitrogen at opposing convection and therefore limiting its spread. The implications of these findings are (1) at higher pO_2 nap propagation becomes the dominant mode of spread and (2) nap propagation will be the dominant mode of spread in the weightless environment. For these reasons we believe that helium is a wiser choice than nitrogen as a diluent. It is more effective at reducing the ignition risk, and it is more effective at reducing the risk of nap fire.

Now let us discuss the behavior of human skin. Previous experiments, you will remember, had shown that flash fires pass over the surfaces of dead pigs and, by analogy, human beings. However, it is obvious that the pig surface is much hairier than that of man, the pigs' skins were only oxygenated from the gas phase, the corpses were not ventilated or perfused and of course also pig fat has a different composition to that of human fat. For all these reasons it could be argued that the pig experiments were not representative. We obtained a square foot or so of human skin and its underlying fat that had been removed from a thigh amputated for ischemic reasons. The skin had been stored in a refrigerator for three days under

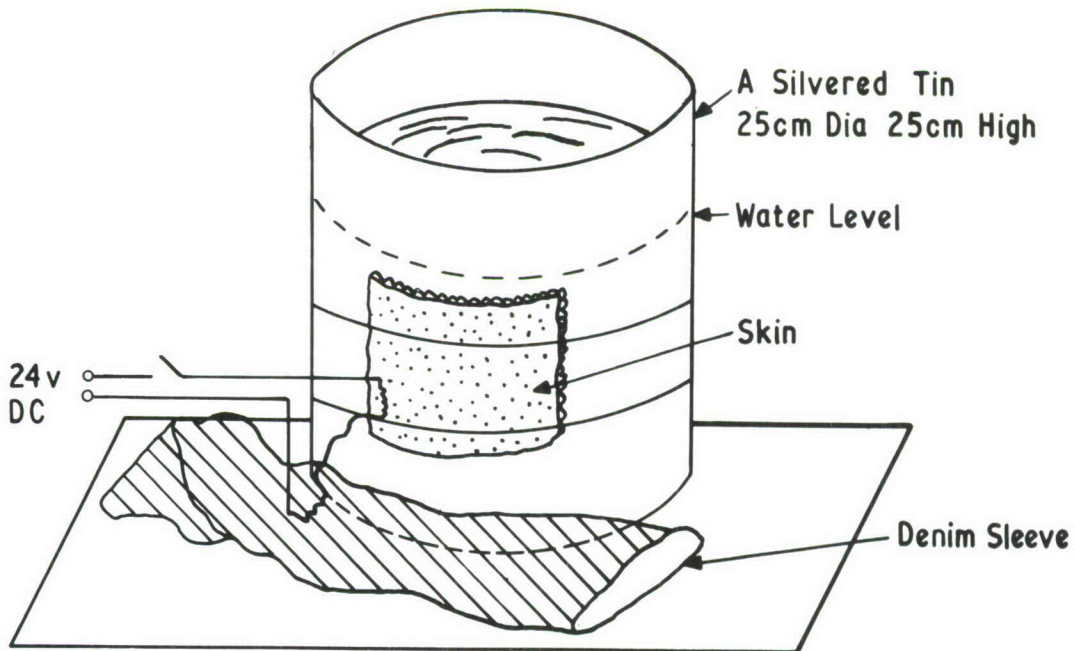
circumstances which could normally keep it surgically viable for three weeks. We felt it could be taken as a reasonable model of living human skin. Because it had been ischemic it was hairless and therefore could not be used for flash fire studies, so we decided to use this trophy to see whether under any circumstances we could make human skin combustible. Figure 3 summarizes the experiments. Perhaps I should begin by telling you that we took a small piece of this skin and held it in a Bunsen flame for five minutes; it slowly wrinkled, charred and reduced itself and occasionally caught fire but the moment it was removed from the flame the fire extinguished itself. So you could say that this skin stored in this manner is not combustible in air at quite high temperatures. In the first experiment we suspended the skin, as shown, above a sleeve and immersed this arrangement in pure oxygen at one atmosphere for an hour. We then ignited the sleeve and after a brief delay the skin caught light and burned like a Roman candle, vigorously spitting flaming fat about it. So human skin could support fire in pure oxygen under some circumstances. However, critics could easily say that this was not representative because the skin was drying out, it was not in contact with a heat sink and fat was exposed at all its edges. In the next experiment we wrapped some skin around a retort stand base (for a heat sink), wrapped a sleeve around the pair and set light to the



(a) This Skin Supported Above A Denim Sleeve Caught Fire After A Brief Delay



(b) This Skin Caught Fire After A Brief Delay



(c) This Skin Was Ignited By The Sleeve But Not The Wire

FIGURE 3. A SCHEMATIC SUMMARY OF THE SKIN EXPERIMENTS

sleeve as before. Once more after a short delay the skin caught light. However, at the end of that experiment when the retort stand was rinsed down, the water hissed suggesting that it had not been a very adequate heat sink after all so we went on to the third experiment (bottom Figure 3). We obtained a tin roughly the dimensions of a human thigh, and filled it almost to the top with cool water roughly at body temperature and firmly wired the skin onto the outside. A sleeve was placed underneath the skin and the ignition coil was passed in such a way that half of it lay in the sleeve and the other half in the skin. When the ignition circuit was closed on this occasion, again having immersed the system for one hour in pure oxygen, the sleeve caught light, and after a delay of a few seconds the skin followed suit; but at no time was it ignited by the coil. The skin once again burned vigorously. We felt that this was reasonable evidence that human skin in contact with an apparently adequate heat sink (the water temperature barely rose), was combustible in pure oxygen. It is still true that fat was exposed to the fire on this occasion.

To summarize, we have learned considerably more about the nature of flash fires. We have studied also the comparative effects of nitrogen and helium as inert diluents and we believe that there are arguments in favor of helium, particularly for space vehicle purposes.

It would be wise to consider human skin as combustible in atmospheres containing oxygen at a pressure higher than 500 mm Hg.

Lastly, I wish to mention our thoughts on fire extinction. We believe, and we have shown, that water in large quantities is an effective extinguisher, but this is obviously an absurd solution for space vehicles. There are two alternative systems which we are dubious about, the first is introducing an inert gas as a quenching agent once the fire has started. From the experiments we have done, and they are admittedly not all that many nor all that well controlled, we have the impression that if you introduce a draught of inert gas the oxygen that it entrains makes the fire worse. I think in slow fires that it is a solution of value, but in very rapid fires this augmentation initially before you get the build up of inert gas, makes the situation worse and not better. The other solution that we have our doubts about, that I believe you have proposed for some space vehicles, is that of opening the hatch and sending the contained oxygen to its eternal doom in space and then at some later time closing the hatch and repressurizing the vehicle with oxygen. Again from our limited and ill controlled experiments, once a fire is established, if you take it up to a vacuum the fire takes a surprisingly long time to go out and for a long time remains sufficiently warm to spontaneously re-ignite when you reintroduce oxygen. You will

probably have to leave it for quite a time. The other thing of course is that it would require, I think, an extraordinarily brave man to open the hatch when his life would depend upon the integrity of a space suit that had been quite near to a fire. From what we have seen of these materials they can quite easily catch fire in oxygen. I am wondering whether they may think it worthwhile to turn to some cooling spray, a liquid nitrogen spray or something like that. If it is delivered at a high pressure you could presumably direct it efficiently even in weightless environments. We have also seen details of a particularly effective foam that does control fire in pure oxygen quite impressively.

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2. Pignatelli, A. B. (1965). A Rapid Response Flame Detection System. Flying Personnel Research Committee Memorandum 228. Ministry of Defence (Air) London.

FLAMMABILITY TEST METHODS AND PROTECTIVE CLOTHING DEVELOPMENT

Mr Richard S. Johnston
Chief Crew Systems Division
NASA Manned Spacecraft Center
Houston Texas

Spacecraft or manned chamber flammability hazards are separable into two major categories; the first category consists of combustible materials capable of sustaining or propagating a fire, and the second category, possible ignition sources.

Major fire sources which normally can exist are electrical, materials auto-ignition or combinations thereof. Electrical fire sources consist of electrical equipment arcing, or short-circuit arcing and/or overload heating. The fire hazard potential of static charge buildup has not been extensively investigated; however, static charge tests have been conducted on Gemini and Apollo candidate spacecraft materials with steps taken to minimize this potential ignition source.

FLAMMABILITY TESTING

The degree of hazard provided by the above sources can be investigated by the following test methods:

A. Short Circuit Flammability Testing - The short-circuit flammability hazard provided by a material in proximity to a shorted wire can be ascertained, for instance, by use of the short-circuit flammability tester shown in the Figure 1 and Figure 1A.

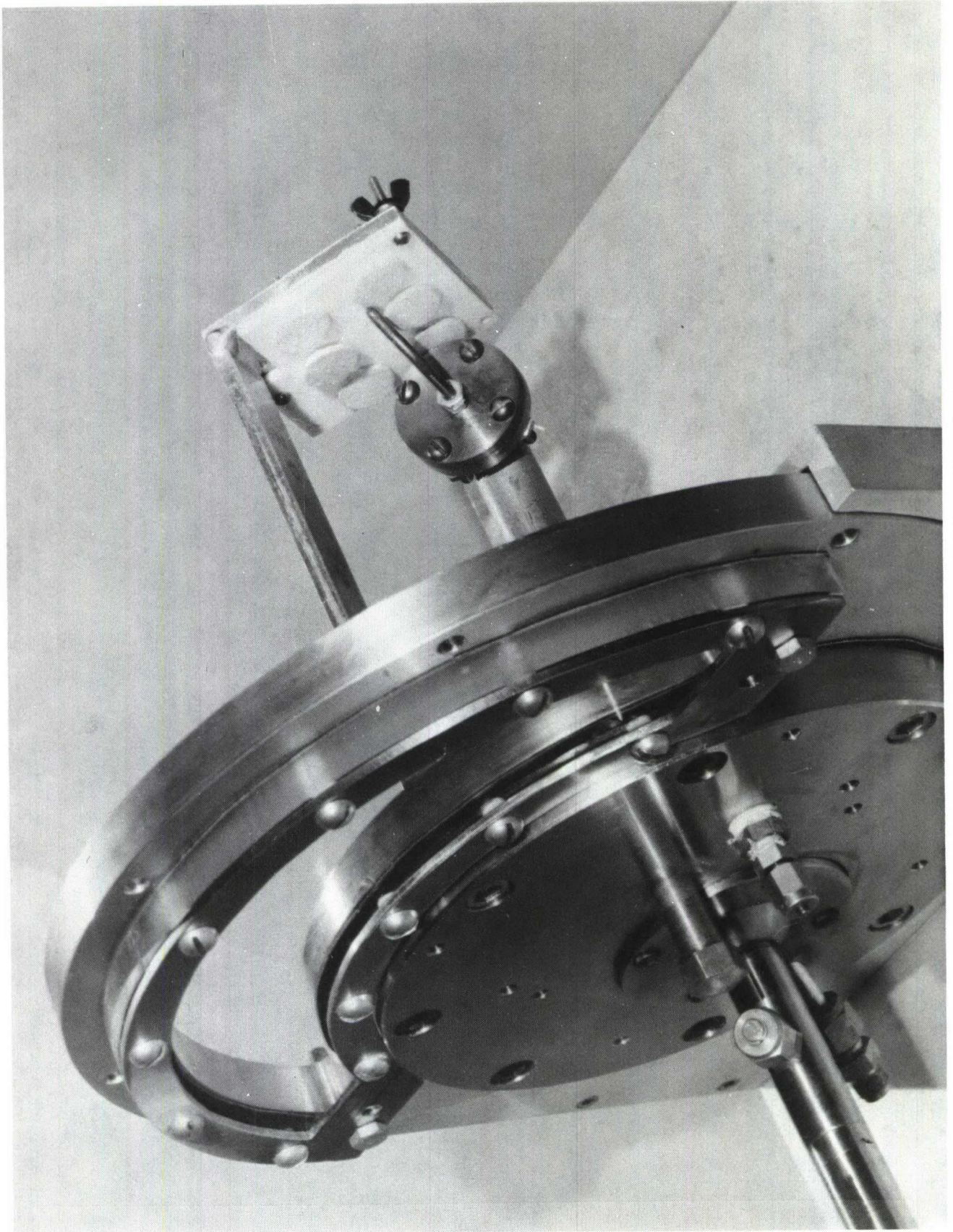


FIG. 1 SHORT CIRCUIT FLAMMABILITY TESTER



FIGURE 1-A

This device, when used in conjunction with a test chamber in an oxygen environment, generates a short-circuit arc of the same magnitude as could be obtained from a particular spacecraft wire--across or near the suspect materials which lie in proximity to this wire. Figure 1A shows the needle electrode which is scratched across the sample to fray it such as could be accomplished by a cut or broken wire, and the short-circuit arc is directed to the frayed area. The minimum current required to cause material ignition at the same source voltage is used, when compared with calculated possible short-circuit current, to ascertain the fire hazard caused by use of the material.

Potting materials and wire insulations are tested for short-circuit overload heating hazard by subjecting wire, in an oxygen atmosphere, to current levels which cause wire failure and verifying that insulation or potting does not ignite.

B. Combustion Rate Determination - Materials are also tested in oxygen environments for flame propagation rates. Materials used in large quantities are required to be noncombustible or self-extinguishing when a vertically mounted sample is ignited at the bottom in an oxygen atmosphere--6.2 or 16.5 psia as shown in Figures 2, 2A and 2B. Ignition is accomplished by a piece of tissue paper (1" x 2") wrapped around a nichrome wire. Small amounts of slow burning

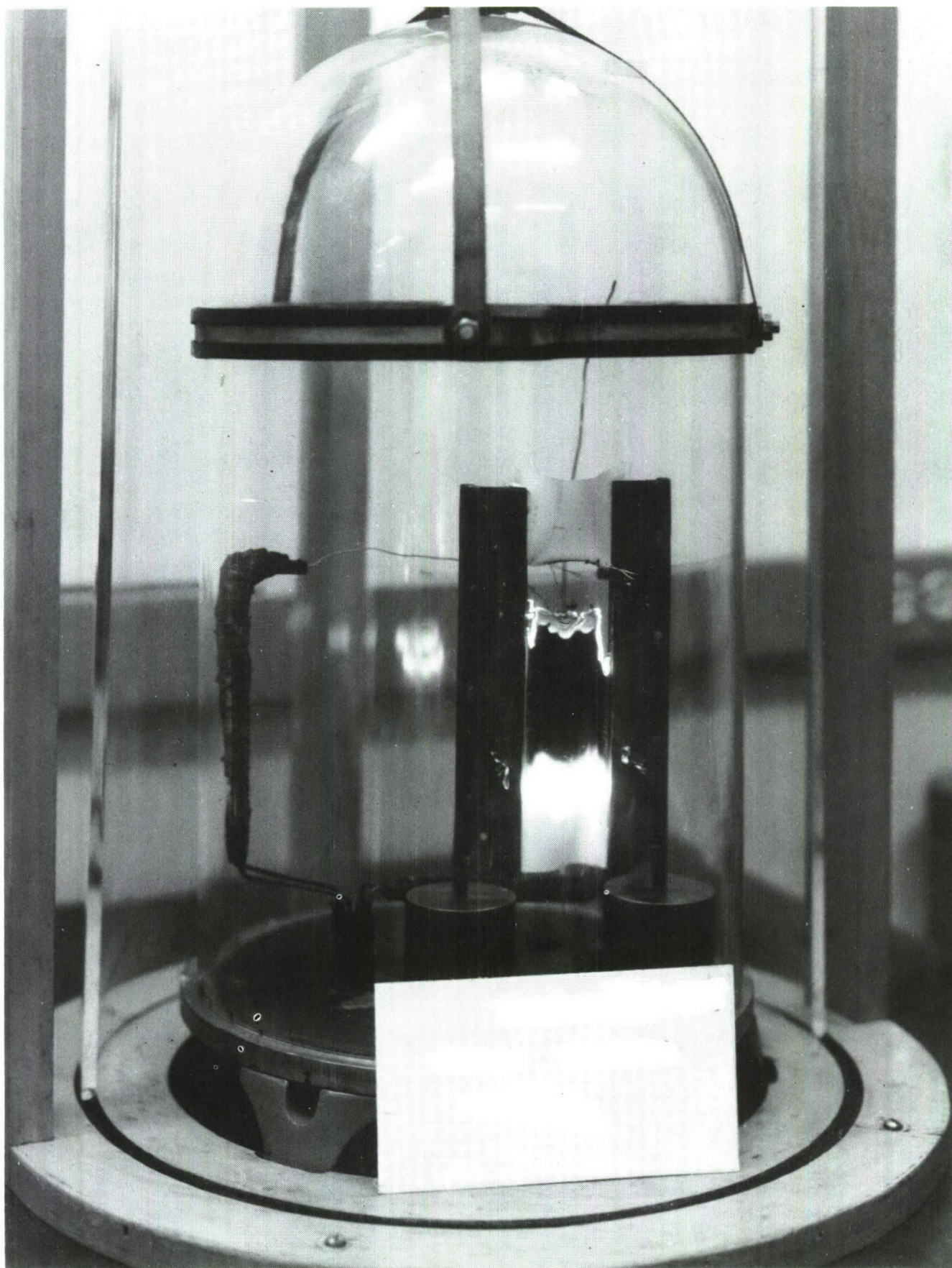


FIG. 2 COMBUSTION RATE TESTER

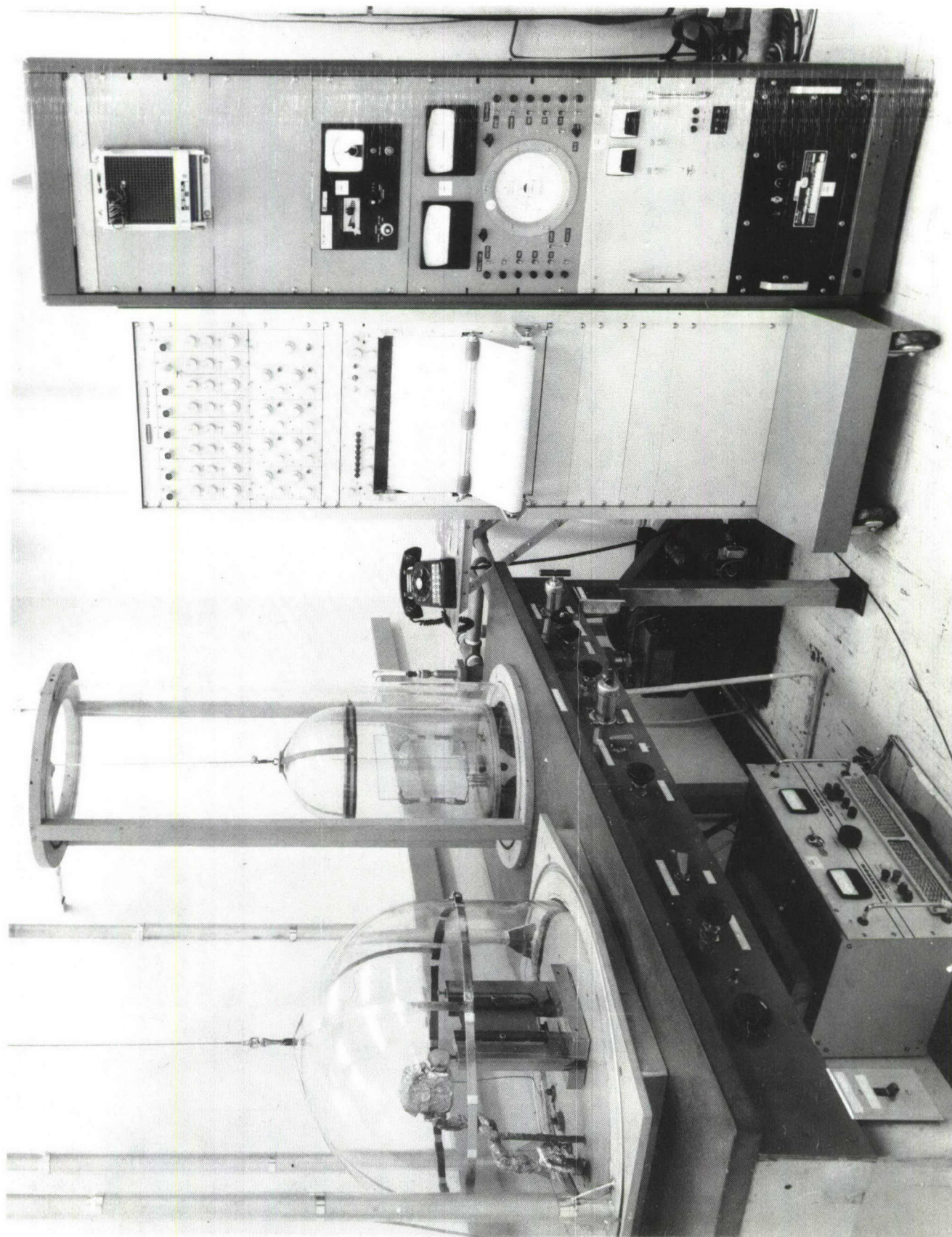


FIG. 2-A. Flammability Tester - Bell Jar (6.2 psia)

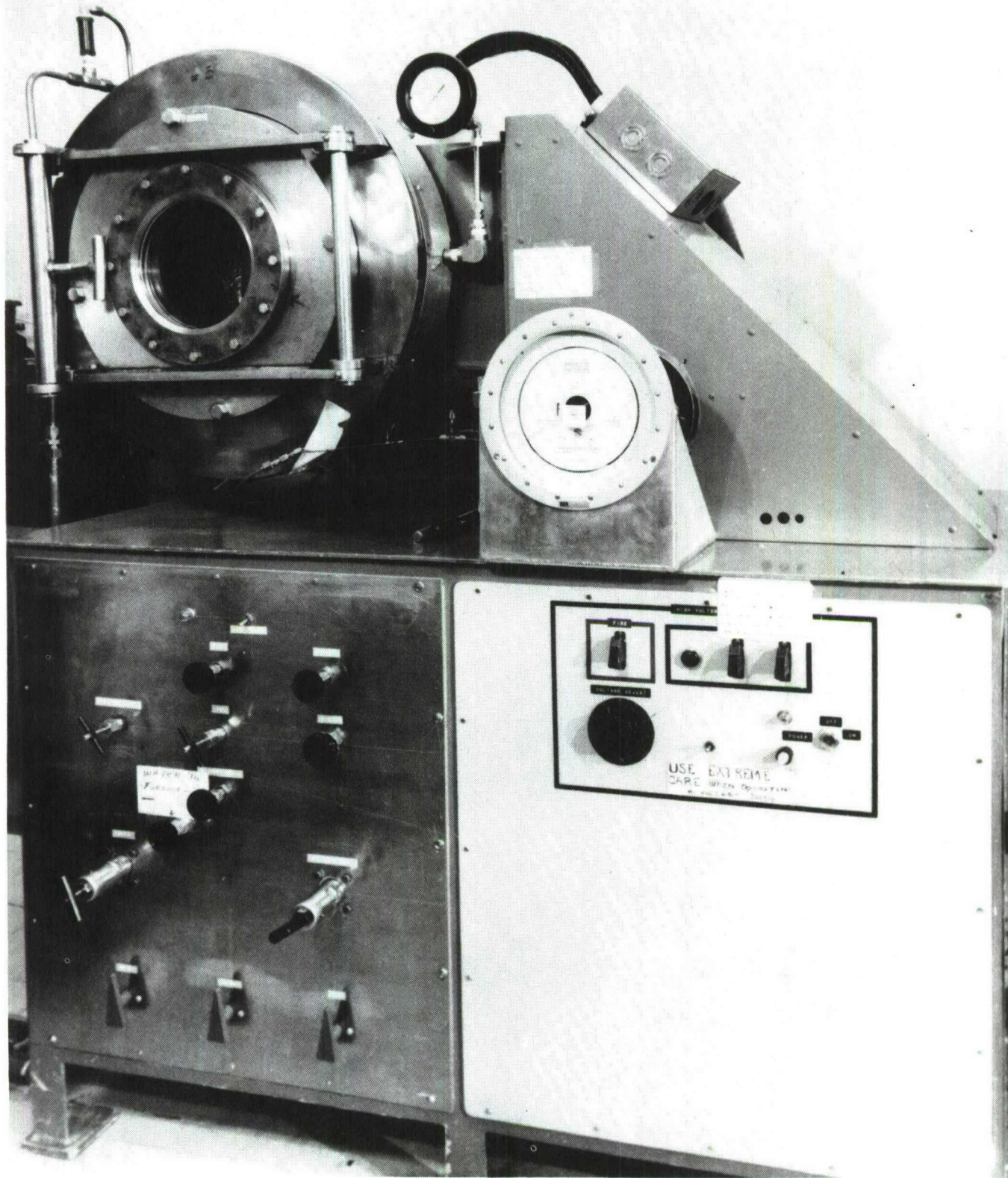


Fig. 2-B. Flammability Test Chamber (16.5 psia)

materials are acceptable, if quantities are small enough to not constitute a fire hazard and if located so as not to provide a serious flame propagation path. Figure 2A shows the bell jar flammability tester (6.2 psia) and Figure 2B shows the flammability test chamber (16.5 psia).

The danger of flash, ignition, or auto-ignition of candidate materials is investigated by use of a tester, an example of which is shown in Figure 3. A sample is mounted in the center cavity and covered with a transparent vicor cylinder. The furnace, capable of controlling temperature of within $\pm 2^{\circ}\text{C}$, is placed over the cylinder and the assembly is mounted inside an environmental chamber and exposed to pure oxygen (16.5 psia). The sample is heated at a controlled rate by use of a remote programmer and a 10,000 volt, 40 millijoule, spark is discharged periodically over the sample surface. Materials must not flash, ignite, char or show other signs of pyrolysis at 450°F to be accepted for flight use.

DEVELOPMENT OF FLAME PROTECTIVE GARMENTS

Flameproof protective garments have been fabricated by NASA's Manned Spacecraft Center, Crew Systems Division. These garments consist of space suits, chamber observer garments, and one- and two-piece flight coveralls. These efforts are directed to alleviate a two-fold need; a garment is needed which will first, be noncombustible, but secondly--and fully as important--be capable of

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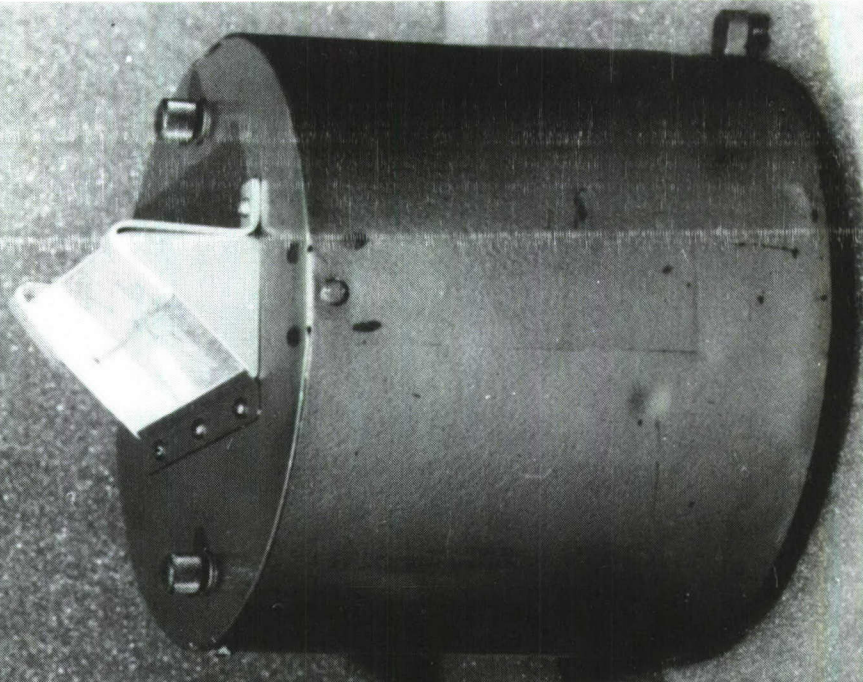


Fig. 3 Autoignition Tester

sustaining a high temperature differential. This ΔT is necessary to protect the crewman against burns and also to ensure no auto-ignition of flammables, such as bio-instrumentation or space suit bladder, contained within the protective layer.

The thermal barrier capability of protective garments is evaluated by use of the flame impingement tester shown in Figure 4. The sample is mounted on the rotating mechanism with thermocouples mounted between each layer. The tester is mounted in a chamber, and the sample is exposed to the required oxygen environment. A flame is initiated in the burner and adjusted to the desired temperature. The flame can be controlled, by adjustment of the gas/oxygen ratio, very accurately--within the accuracy of the measuring thermocouple. Flame temperatures of 1200°F and 1800°F are most commonly used. As the sample is remotely lowered over the burner, a relay is actuated, which opens a shutter and instantaneously exposes the sample to the open flame. The resulting temperature vs time curves are used to evaluate the usefulness of each layer and the effectiveness of the layup as a whole. Figure 5 shows data taken on a candidate space suit layup. Note that, upon direct impingement with an 1800°F flame, the pain threshold was reached in 35 seconds and the bladder material decomposition temperature in 150 seconds.

Materials being evaluated for protective garment construction

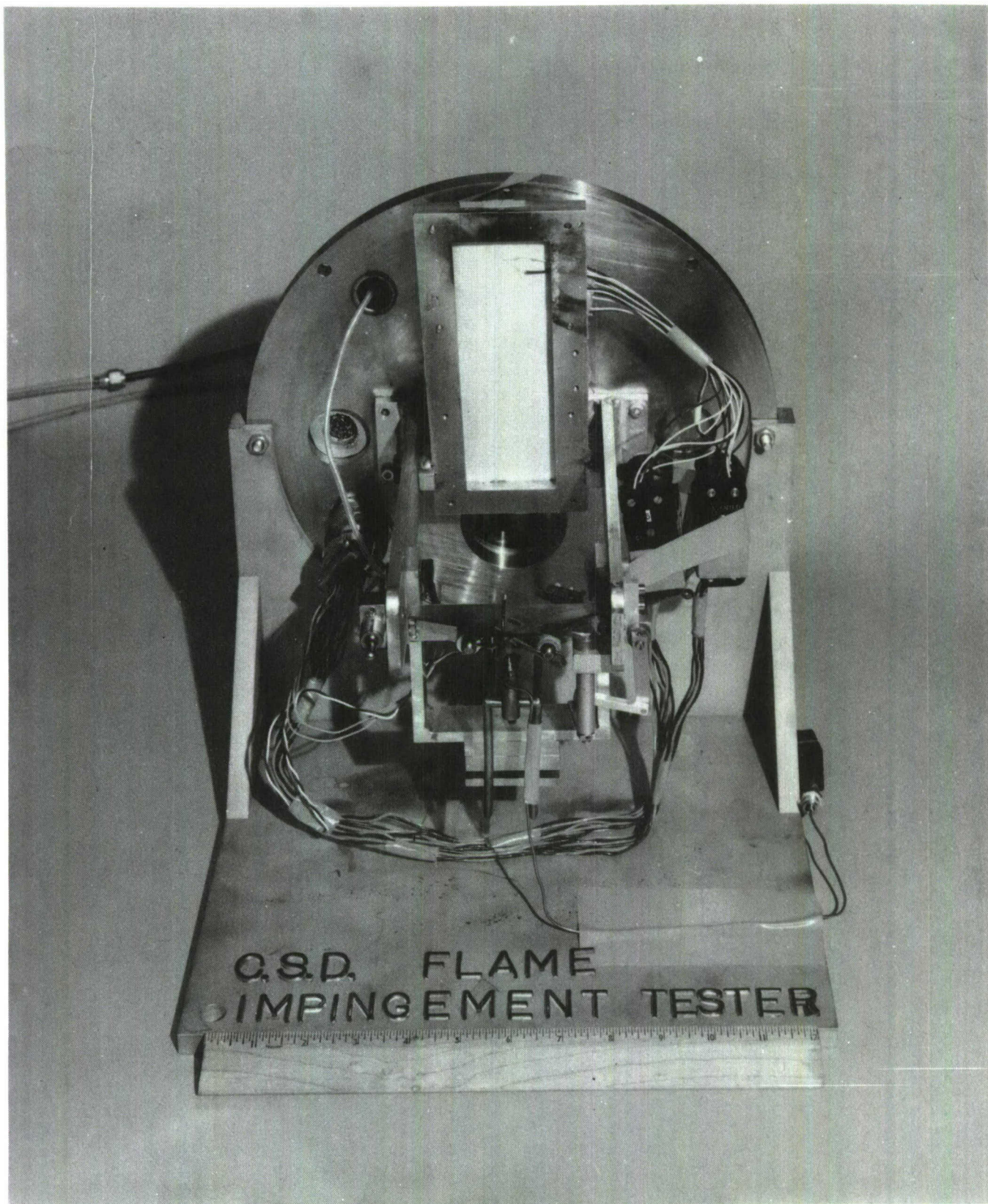


Fig. 4 Flame Impingement Tester

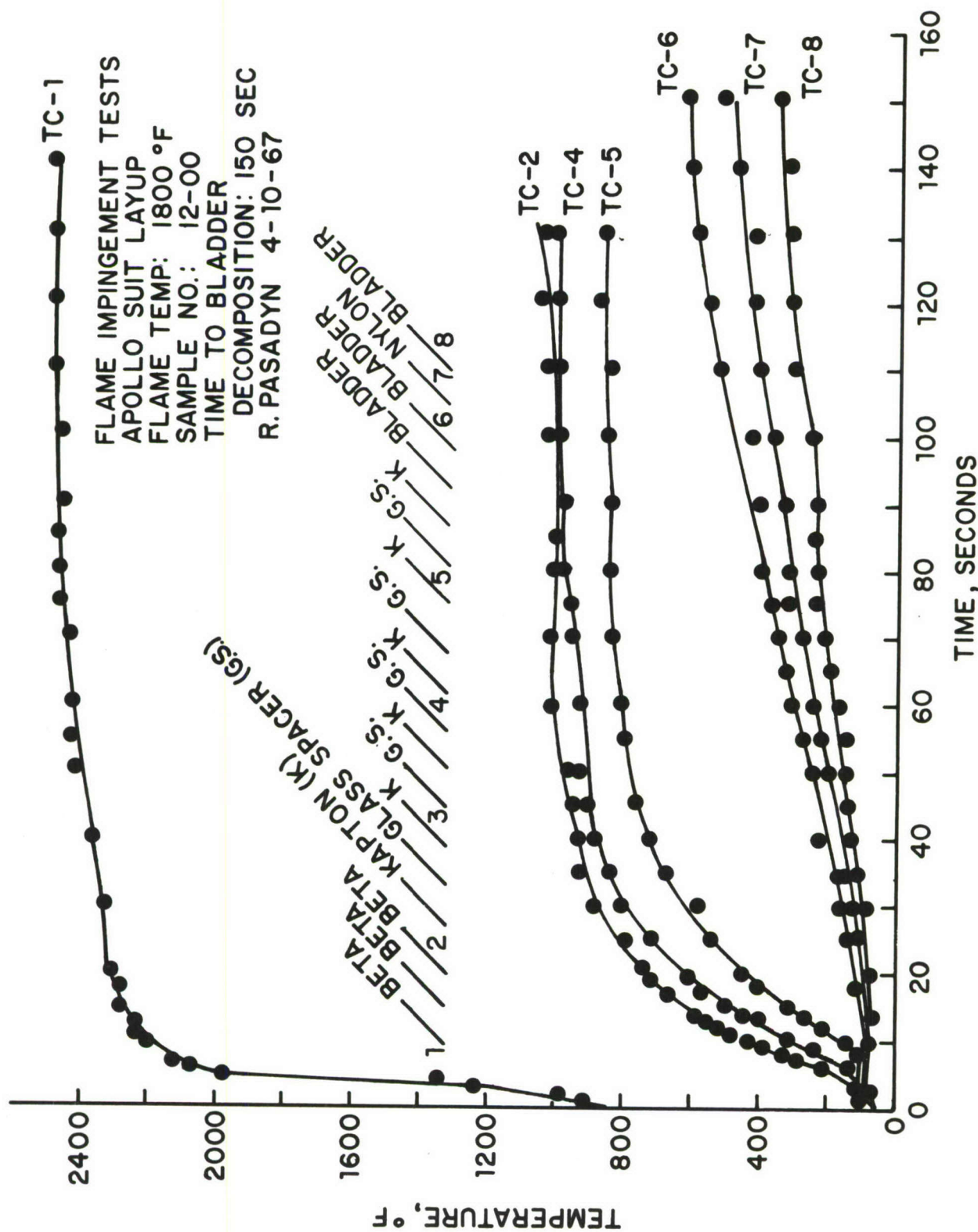


Fig. 5 FLAME IMPINGEMENT TESTS - TIME / TEMPERATURE DATA
 ON CANDIDATE SPACE SUIT LAYUPS

are beta fiber cloth, armalon, asbestos, kapton, metallic fabrics, and melds of asbestos, beta, and metallic fibers.

Beta, a 3.8 μ filament glass fabric, is the material now being considered for outer layers of all protective garments. It is also available in cords, braids, tapes, and webbings. This material, though completely nonflammable, does not possess the same abrasion resistance as nylon has (about 1/8 as abrasion resistant as nylon) and requires reinforcement or replacement with metal fibers in areas of high abrasion to increase its service life and minimize the quantity of abraded beta particles loose in the cabin. Special sewing techniques are required for use with beta, but good seams are possible. Special webbings are being fabricated of beta in which inserts of nylon fiber or metallic fibers are woven into areas which are to pass through high abrasion hardware, such as buckles and "O" rings. Underwear made from beta fiber such as shown in Figure 6 has been evaluated and found to have no adverse dermatological effects and to have excellent vapor transmission properties. Initial protective garments were fabricated using Owens-Corning specially designed X4190B beta material. The chamber observer garment and flight coveralls shown in Figure 7 through Figure 7C is an example of our first effort garments. This garment is nonflammable; but, because of its light weight, it does not provide a sufficient thermal barrier.

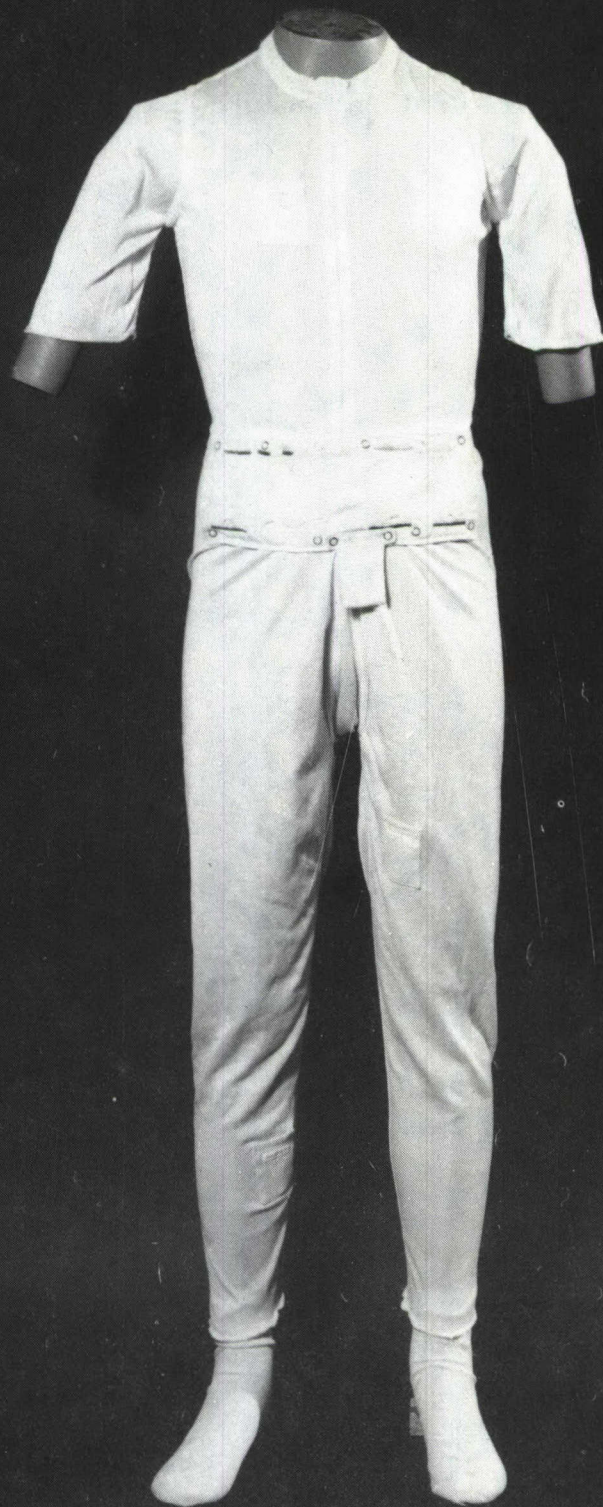


Fig. 6 Constant Wear Garment

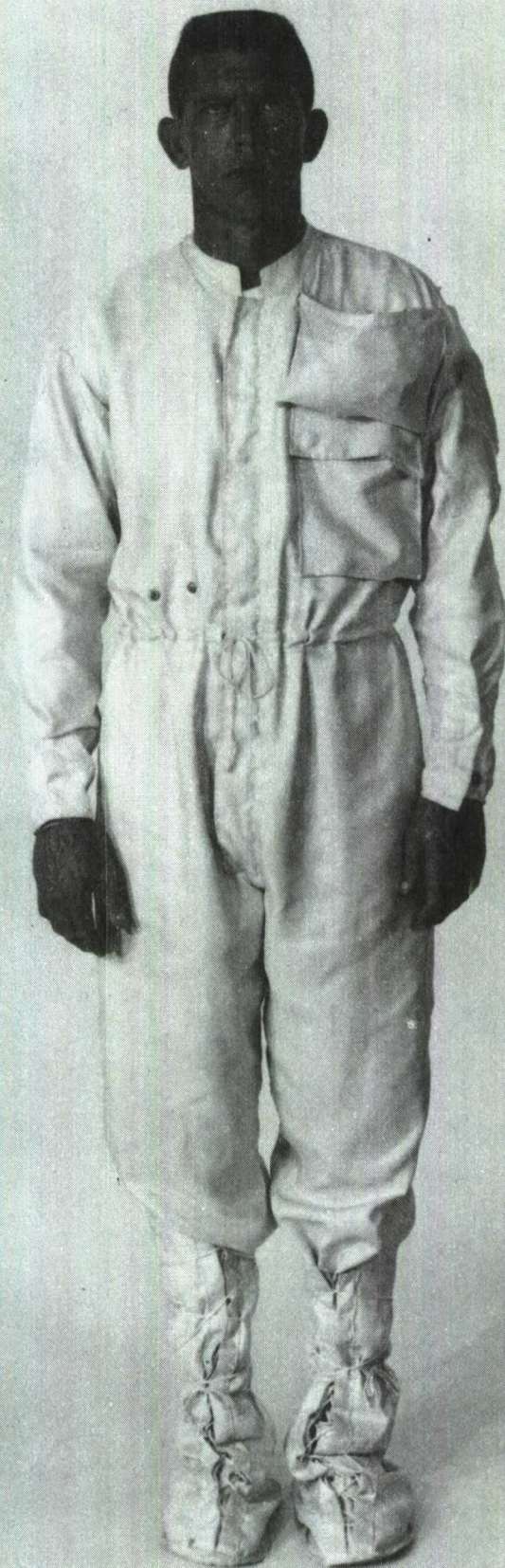


Fig. 7 Chamber Observer Garment



Fig. 7-A Chamber Observer Garment with Hood (Front View)



Fig. 7-B Chamber Observer Garment with Hood (Back View)



Fig. 7-C Flight Coverall

The hood, stowed in an upper pocket, as shown in Figure 7, is slipped on, Figure 7A, prior to going into a fire hazard area. It is supplied with a combination Chemcor-Pyrex visor. Flame impingement tests have indicated that asbestos and asbestos/aluminum provide very good thermal barriers. Figure 8 shows three suit layups. Sample Two is similar to Sample One, except for the addition of one layer of 3-mil aluminum. As Figure 9 shows, one layer of aluminum improves the thermal barrier properties immensely. Existing aluminized materials are not satisfactory for this application because of the flammable adhesives used. NASA MSC CSD is investigating the development of a nonflammable adhesive from carboxy nitroso polymer, which may allow bonding of aluminum to beta or asbestos.

Asbestos does have the disadvantage of poor tensile strength and sewing qualities. This shortcoming is being overcome by a development effort for melding asbestos, beta, and other fibers in an attempt to increase total fabric strength. This effort should result in a bulky cloth of about 13 oz/yd² with excellent thermal properties. These fibers will also be incorporated into a "composite" fabric. This fabric will have one surface which is predominantly continuous filament, nontexturized beta; and the other surface will be soft, bulky, and fibrous. The hard surface will be used on the outside of a garment where abrasion and snagging problems exist.

FLAME IMPINGEMENT TEST

NASA - MSC, Crew Systems Division

May 9, 1967

CANDIDATE INTEGRATED APOLLO SPACE SUIT LAYUPS

Thermocouple

Bladder
Nylon
Bladder
Bladder
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
Glass Spacer
Kapton
Beta
Nomex
Beta

Flame

Bladder
Nylon
Bladder
Bladder
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
Nomex
Beta
Beta
Asbestos
Asbestos
Asbestos
Beta

Bladder
Nylon
Bladder
Bladder
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
G.S.
Kapton
Nomex
Beta
Beta
Asbestos
Asbestos
Asbestos
Aluminum Foil
Beta

SAMPLE No. 1

SAMPLE No. 2

SAMPLE No. 3

Figure 8

G.S. - Glass Spacer

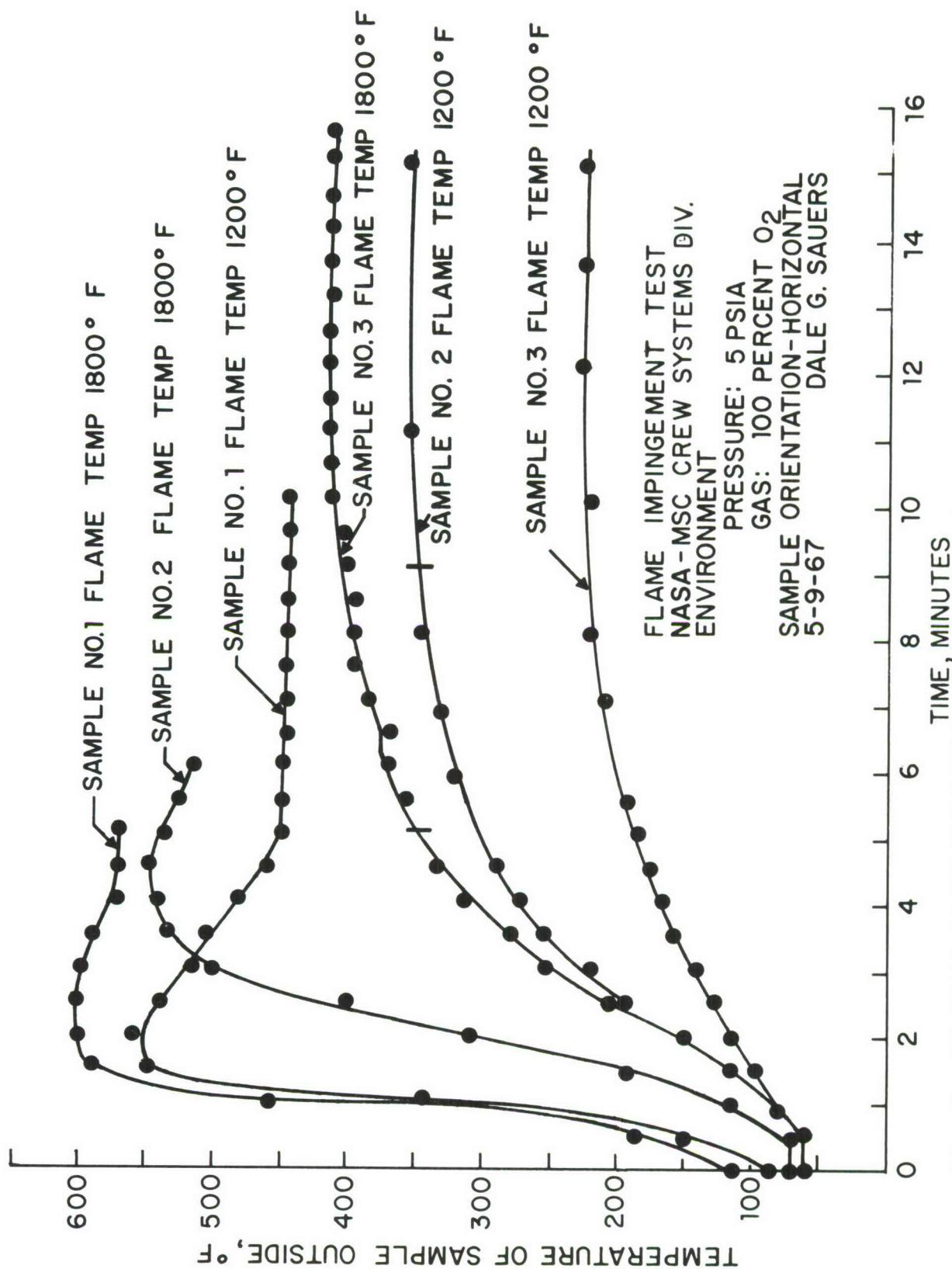


Fig. 9 FLAME IMPINGEMENT TESTS - TIME/TEMPERATURE DATA ON CANDIDATE SPACE SUIT LAYUPS

Still another material being developed consists of an asbestos web sandwiched between two layers of beta fabric. The layers are mechanically linked by use of an arachne machine and glass thread. The design goal for this material is a $1600^{\circ}\text{F} \Delta T$ after 30 seconds exposure to an 1800°F flame in a 19 psia oxygen environment.

A final material under development for use in protective garments consists of a combination of beta and chromel-R metallic fibers. This constitutes an effort to increase the tensile and abrasion resistance of beta fabric. This material will be available in fabrics, webbings, cords, braids, and tapes.

Though protective garments are a small portion of our materials effort, NASA MSC CSD is investigating other materials in an effort to obtain nonflammable protective garments which will provide greater comfort and safety in potential fire areas. In addition, this effort will, hopefully, result in garments with increased abrasion resistance for greater durability. These efforts will include development of Quartz, Boron Nitride, and other inorganic fabrics, nonflammable, high-impact visor materials, and nonflammable elastomers and adhesives for use in garment construction.

PANEL DISCUSSION

Moderator	Col A. G. Swan	Aerospace Medical Division
Members	Mr B. P. Botteri	AF Aero Propulsion Laboratory
	Capt D. I. Carter	Aerospace Medical Division
	Dr Fred Dawn	NASA Manned Spacecraft Center
	Flt Lt David Denison	Royal Air Force
	Mr L. A. Eggleston	Southwest Research Institute
	Mr T. E. Goonan	Veterans Administration
	Lt Cdr J. V. Harter	US Navy Experimental Diving Unit
	Dr Karl Scheller	Aerospace Research Laboratory
	Dr A. A. Thomas	6570 Aerospace Med Rsch Labs

Mr R. L. Burley - CGS Scientific Corp - Southampton Pa

I have a question of Dr Thomas. On his last film, what direction were your nozzles pointed? Were they varied in angle or were they all pointing down from the top?

Dr A. A. Thomas

We had five nozzles pointing in a certain angle, closed in so that we get most of the water into the floor area. You see the Domes have a tilted side, we did not feel that there is much payoff in directing half the water on the perimeter. There are five regular heads positioned in a diamond shape. They are not automatically fused.

Questioner not identified

Dr Thomas, why did you ignite the clothing inside rather than the outside?

Dr A. A. Thomas

We did not. The nichrome coil was on the outside of the coverall. Now the 3.2 seconds delay of the water made it burn through. When the water was turned on, it could not wet the inside where the fire was creeping.

Dr Thomas Allen - USAF School of Aerospace Medicine - Brooks AFB Tex

Dr Thomas, do you have a reference to the tolerable, permissible concentration of hydrogen fluoride for human exposure?

Dr A. A. Thomas

Yes sir. There have been limits set by the National Academy of Sciences' National Research Council for short duration exposures to HF and also for fluorine. By the way, regarding the mortality which you get from the pyrolysis products of CF_3Br , the slope of the curve overlays exactly that of hydrogen fluoride so I would say 90% of your mortality is due to pulmonary damages due to hydrogen fluoride.

Dr Thomas Allen - USAF School of Aerospace Medicine - Brooks AFB Tex

Question was not audible on tape.

Dr A. A. Thomas

That concentration of hydrogen fluoride as a pulmonary irritant will probably not do serious damage in twenty-four hours. I would hesitate to expose a person to that kind of an atmosphere for a week or two weeks. As is with most pulmonary irritants, there is a certain

tolerance developed against them if you apply them at a very low dosage level. We did exposures to NO₂, which is a fine pulmonary irritant, for ninety days continuous at the present American Industrial Threshold Limit Values. There was no pathology in those animals.

Dr Gerhard Cook - Union Carbide Corp, Linde Division - Tonawanda NY

Did you get the nap fire before the water was turned on?

Dr A. A. Thomas

You could not see the ignition coil as it was positioned on the opposite side of the dummy from the camera. We just lucked out and most of the fire burned on the rear--on the side adjacent to the camera. The nap fire burned before the water was turned on.

Speaker unidentified

Lt Denison, you mentioned that probably we should design our water spray system in some particular manner. I wonder if you could give us some guidelines to follow in designing the water system?

Flt Lt David Denison

We believe that water sprays should be designed so that they deliver five milliliters per square centimeter per minute regardless of direction. It must be established in all directions. Having one such system you must also include a hand held water spray because there will inevitably be some areas of the body and some areas of the chamber that will be shielded from any fixed spray system that you can construct.

Speaker unidentified

Question was unidentifiable but pertained to development of an atmosphere which would least support combustion.

Capt D. I. Carter

I think it is safe to say that we will be looking at several aspects of this. One will be whether or not we can maintain a small concentration of some flame inhibitor as a normal or constituent gas in a spacecraft environment--perhaps a standard concentration of perhaps 30%, maybe 45%, Freon 1301 in a high oxygen environment. There are all sorts of Freons, some of which are quite toxic. We will have to judiciously pick those that we attempt to use in this manner.

Dr A. A. Thomas

I am sorry there is confusion on Freon. When we say 860,000 ppm, we said for fifteen minutes. From what we know about the others, like chlorobromomethane, in long term inhalation studies in animals, you start picking up, in the case of chlorobromomethane, blood levels of bromine with a tranquilizing effect and a loss of appetite at 500 ppm if administered for only six hours a day, five days a week for six months. I have no feeling at the present what will happen with CF₃Br. It is very hard for me to imagine putting people in an atmosphere like that without having some chronic animal inhalation data.

Flt Lt David Denison

I have a comment. I do not want you to be misled by Dr Thomas' work. You saw in his experiments a large sheet of flame and a small percentage degree of destruction. It could be misleading to accept the small degree or percentage of destruction from a technical viewpoint. That sheet of flame was easily intense enough to damage a very large area of skin. This is precisely why in our experiments we took as a measure of severity, the time to 50% and to 100% obscuration of the dummy by flame, and, I think this is most important in the future experiments. The second thing is something that Dr Strughold suggested to me which is that it might be worthwhile to agree on a fixed term for this nap fire so that everybody knows precisely what is meant. Flash fires mean ten things to ten people. I wonder whether perhaps nap fire or nap propagation would not be a term that we could agree on.

Question not recorded

Col A. G. Swan

Dr Denison, I also wanted to ask you about this same thing. In the water distribution you are referring to water coming from all directions, are you not? In this chamber, in this last demonstration that you saw today, water was coming from overhead at approximately 30 milliliters per square centimeter per minute.

Flt Lt David Denison

Yes sir. It is against any surface. You should be able to collect 5 ml per square centimeter regardless of the inclination of the surface. The way we measured this was with rectangular tins in arrays. When we have made a vertical stack in the position of the dummy and achieved at least 5 ml per square centimeter everywhere, then it controlled the fire on the dummy.

Col A. G. Swan

He is still with 5 milliliters per square centimeter but in the terms of reference Dr Denison may have a great deal more water than the density which we use because we consider only the surface area of the floor and he considers all surface area in the chamber.

Flt Lt David Denison

We have not done enough experiments to answer that. All I can say is that the most severe atmosphere we have considered--pure oxygen at 15 psi--this density works, 3 - 4 is the minimum and 5 the safe maximum.

George Mumma - Martin Co - Denver Colo

Is there any work to date concerning the effects of zero-G on fire propagation, ignition or otherwise, or is there a problem in the area?

Col A. G. Swan

There has been some work done on that by NASA. I have a report

on it that I just received in the mail the other day. I do not know the details of the report at all. NASA sponsored some work that was done in the KC-135 at Wright-Patterson AFB flying very short term zero-G parabolas and I will be glad to give you that reference if you like.

Capt D. I. Carter

Sir, I believe Mr Kimzey who did that work is present. Will he hold up his hand please.

Questioner unidentified

Question pertained to overpressure in a chamber subsequent to release of Freon.

Capt D. I. Carter

We have done this in the low pressure chambers. We started out at either 258, 380, or 600 mm Hg pressure in the chamber and when we released the Freon, only on the last test did the Freon raise the pressure to ambient. We still had less than atmospheric pressure in the chamber except on the last test. In the hyperbaric chamber, the high pressure chamber, we would start at say 75 psi pressure and then dump the Freon into the chamber. The chamber pressure would immediately decrease to say 72 or 73 psi due to the evaporation and cooling effect of the Freon. Then as soon as the Freon equilibrated, temperature wise, the pressure would go back to about 77 to 78 psi.

Col A. G. Swan

Are there any other comments.

Mr L. A. Eggleston

When we first started planning these tests we anticipated that when the Freon was discharged there would be a very rapid increase in pressure. We anticipated that since we were working with about 50% oxygen and 50% Freon after discharge that we would get a very quick doubling of pressure. It did not work that way. Immediately after the discharge we could see a very sharp, short pressure wave, I do not think it lasted more than a millisecond or so. We could not get very good records on that because the pressure transducer was connected to a Sanborn recorder and the instrument was not fast enough to record the pressure wave. We got about 50 to 75% of the indicated pressure rise in the first half second to one second then the vaporization of the rest of the Freon, which would bring it up to doubling the pressure, occurred over anywhere from 15 to 30 seconds. Now that was where we discharged the Freon out into the chamber. The only thing that could vaporize the Freon was the heat available in the chamber, which was not much. In the last series of tests in the hyperbaric, we directed the Freon against the steel walls of the chamber. We noticed that it vaporized much more rapidly than when it was discharged free into the center of the chamber and it is entirely

possible that had this been done in the earlier tests we would have seen more of a pressure increase than we actually did.

Peter Hasslacher - Hamilton Standard Div, United Aircraft Corp - Windsor Locks Conn

We have talked today about fires in an oxygen atmosphere in a chamber. I was wondering whether you care to comment on a little different situation--a fire in a spacesuit in an evacuated chamber where you have oxygen in the spacesuit being supplied by a back-pack. If you had a fire in that situation, my question is what would you do?

Flt Lt David Denison

The best method is to not have the fire.

Col A. G. Swan

I think Dr Denison's answer to that is about as good an answer as you will get--avoid it.

Bill Riehl - George C. Marshall Space Flight Center - Huntsville Ala

In answer to that last question (remainder not recorded).

Col A. G. Swan

He said that they have done some work over at NASA and the conclusion is that there is really very little chance for anything to start a fire except the bioinstrumentation and that there would have to be considerably more current passing into the pressure garment

than is available to start a fire. Design is the most important thing that you can do in order to preclude this sort of thing.

Questioner unidentified

Does the water put out the fire by cooling down the fire or by removing the oxygen from the fire?

Col A. G. Swan

You are doing two things. First, you are lowering the temperature around the garment, and secondly, you are increasing the ignition temperature.

Flt Lt David Denison

Getting back to your question. We have given some thought to getting a fire inside an impermeable piece of clothing and we wondered whether it might not be possible to build a foam system into the suit. The weight of powder required will be quite small and you will want an additional small amount of water which will then enclose you in foam. It seems quite a reasonable approach to an otherwise very difficult problem.

Wg Cdr Allen Crawford - Royal Air Force, British Embassy - Wash DC

All the full pressure suits I have seen have been well ventilated. It might be possible to consider having a Freon source or something like that which fits into the ventilation system inside the suit. It may not work but it might be a better answer than just avoiding it.

Unidentified speaker

Suggested use of nitroso rubber in pressure suits.

Col A. G. Swan

Right. Nitroso rubber appears very promising in removing the flammability in pressure suits.

Mr L. A. Eggleston

I would like to indorse Col Swan's analysis of how the water spray works. Certainly during the early stage of the extinguishment it is a matter of cooling and after that the wetting of the material is highly important. We feel right now looking at the data, at least that is my personal opinion, that if we had a smaller water droplet at a higher velocity we probably could put out the fire a little bit faster.

Lt Cdr J. V. Harter

I would like to bring up one thing--in all the films that you have seen there has been, as I see in the films, one piece of flammable equipment in the whole chamber. In the fire that we experienced, within fifteen seconds we had nothing but a glow of light inside the chamber. I imagine that was similar to the Apollo fire. As long as I see movies where water is being admitted for four minutes and flame continues to be there, I do not think we have a favorable extinguishment system. We are making a test on one single article, and I think

you have to consider a closed space for two or three people who are jammed right in together with many materials around. Even with all the work that has been done in material selection, I do not believe that NASA or the Air Force or the Navy really are in a position, of course I may be wrong there, but I do not believe that the materials are there and the knowledge is there to fully implement a system where you have nothing that burns. I believe that when you put all this together in a chamber that is maybe 5' in diameter because you are not going to orbit earth in these 12' chambers, cram it in together, and you have a source that starts burning and you turn on the water, I think you are going to be able to transfer this flame to other parts of the chamber. I think tests along these lines need to be done before we can come out smelling like a rose and say that we have licked this problem.

Col A. G. Swan

There is one thing that I would like to acknowledge and that is if you take the approach that you remove all flammable materials and if you remove all ignition sources, you make it quite impossible to do any research with the materials that are available to us today. This is an unreasonable approach to go to this extreme, certainly in the type of chambers that we have and I quite agree with you that we have a long way to go before materials are adequate and as versatile

as they need be to satisfy all the needs that go into a chamber and certainly in a spacecraft, it is a great deal more restricted.

Capt D. I. Carter

We did a couple of tests in which we had more than one garment in the chamber. The two pig tests you saw this morning were a poor representation because one of them was in a fiberglass uniform. We have had two cotton cloth uniforms in the chamber in which we did a test at 600 mm Hg and we put it out satisfactorily. Of course this was just two pieces of material.

Col A. G. Swan

And the chamber was devoid of other flammable materials.

Mr L. A. Eggleston

I would like to make an additional comment. Both the systems that we have worked with were not intended to direct their efforts on a single spot fire. I think they would have worked equally well no matter where in the chamber the fire was placed. The only reason we placed the fire where we did was so that we could get a good record of it with the high speed camera and the TV monitor. As far as the actual extinguishment is concerned, take your pick.

Mr Thomas E. Goonan

Certainly these systems are subject to false operation. A proper design for any chamber would be to analyze the ambient

light sources and provide filters to remove the common sources that will actuate the system. I do not believe that any off-the-shelf detector would be used in a hyperbaric hospital chamber without some modification, at least filtration. If you have a gangrene patient, or more particularly, a patient on the table, it is very important that you do not have an accidental operation. I believe that we should have multiple detectors, say six or eight--depending on the size and shape of the chamber, and the circuitry arranged so that the system would operate from any two detectors. That would remove some of the false operations but we would have to be careful that we did not defeat the system by doing this.

Mr L. A. Eggleston

I might add that the choice of a detector and its sensitivity is just a matter of arithmetic. The sensors that we have used here are made by Thomas A. Edison at West Orange, New Jersey. It is a fairly standard cell with a sensitivity that ranges between 1900 and 2900 Angstroms. The upper edge of the visible spectrum is around 4,000 Angstroms, so you have a pretty good range between the ordinary ambient light and the sensitivity of the detector. Now, if you compromise that and bring in some ultraviolet source, it is entirely possible that you can trip it and get a false operation. But certainly any system like this should be adequately safeguarded by standard

operating procedures. It amounts to a design and operating consideration.

Flt Lt David Denison

Going back to the hyperbaric chambers, the majority I believe are still pressurized with oxygen and not with compressed air. One thing that we have found out, I do not know if you have the same here, is that there is a type of one man chamber that consists of a lucite cylinder some 24" in diameter into which the patient is slid. A clothing fire in such a chamber has enough energy to ignite the lucite cylinder. This is strenuously denied by the makers but irrefutably proved by the experiment. If the lucite coat were to melt, you would finish up like a flying ember.

Questioner unidentified

Question pertained to the quantity of water required.

Col A. G. Swan

When you can hook into the San Antonio city water supply and have a drain in the chamber you are in good shape, but if you are talking about taking a water system into space, you are talking about a different proposition.

Questioner Unidentified

Ultraviolet detectors require an open flame to give a signal. I wonder if there is need for a detector which will detect an incipient

overheated condition or fire that may be in a compartment or in some other shielded location where the UV detector would not pick it up immediately.

Col A. G. Swan

I will be glad to answer that question. There is a need for improved sensors and detectors. There is no question about that. We have taken things that were available "off-the-shelf" and we have adapted them to the particular situation. We would hope that as a result of conferences such as this, our attitude has been one of trying to exchange information between knowledgeable groups, the state-of-the-art in this entire area would be advanced.

Questioner unidentified

I noticed this morning that Mr Botteri ruled out the use of temperature sensors. I wonder what his reasons for this might be.

Mr B. P. Botteri

The only reason I ruled out temperature sensors was with respect to the use for total chamber surveillance. Temperature sensors located in small compartments where you might expect more localized fires would probably be adequate for protection. As far as trying to oversee an entire volume, they would be rather slow compared to the flame radiation surveillance detectors. For the type of system that we are designing at Brooks, we thought that the radiation sensors would

definitely have an advantage. For space vehicle application the over heat detectors might have definite applications especially behind electrical control panels and things of this sort.

Col A. G. Swan

Do we have other questions? If not, thank you very much.

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Aerospace Medical Division Air Force Systems Command Brooks Air Force Base, Texas		2a. REPORT SECURITY CLASSIFICATION Unclassified	
		2b. GROUP	
3. REPORT TITLE Proceedings of Fire Hazards and Extinguishment Conference			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Special Report			
5. AUTHOR(S) (Last name, first name, initial)			
6. REPORT DATE May 1967		7a. TOTAL NO. OF PAGES 206	7b. NO. OF REFS 20
8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. d.		9a. ORIGINATOR'S REPORT NUMBER(S) AMD-TR-67-2	
		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
10. AVAILABILITY/LIMITATION NOTICES Distribution of this document is unlimited. It may be released to the Clearinghouse, Department of Commerce, for sale to the general public.			
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY	
13. ABSTRACT Subsequent to the fire in the space environment simulator at Brooks Air Force Base on 31 January 1967 the Aerospace Medical Division developed fire extinguishing systems and protective clothing for use in oxygen enriched atmospheres. As this was a subject of intense general interest, it seemed appropriate to host a conference to describe and demonstrate these fire extinguishing systems and protective clothing. This document contains the proceedings of the conference which was held on 23 May 1967 and was attended by approximately 300 persons.			

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Space environment simulator Combustion in oxygen enriched atmospheres Toxicity of halogenated hydrocarbons Protective clothing for oxygen enriched atmospheres						

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